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CEL BUILDING AND EXPERIMENTAL SUBGRADE COOLING SYSTEM, BARROW, --ETC(U)
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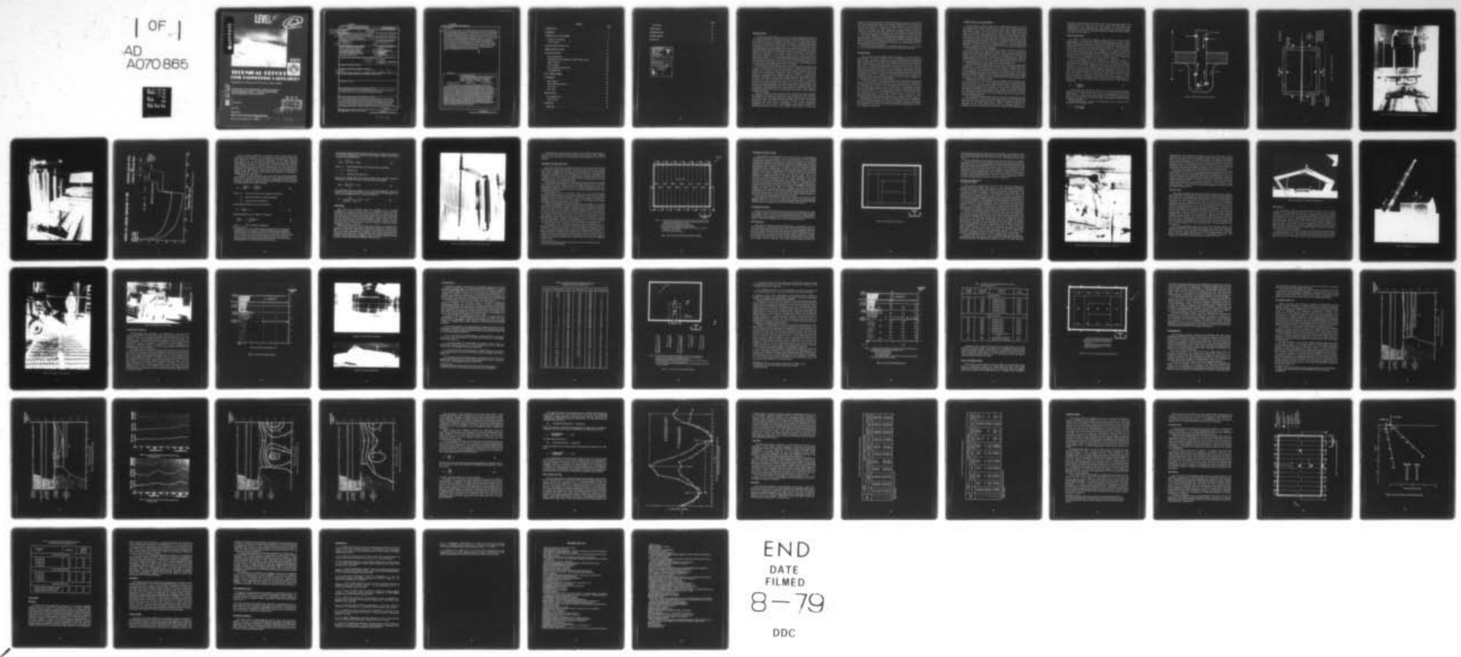

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TECHNICAL REPORT
CIVIL ENGINEERING LABORATORY

Naval Construction Battalion Center, Port Hueneme, California 93043

CEL BUILDING AND EXPERIMENTAL SUBGRADE COOLING SYSTEM, BARROW, ALASKA – CONSTRUCTION HISTORY AND PERFORMANCE CHARACTERISTICS

By

J. L. Barthelemy

March 1979

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER 14 CEL - TR-870	2. GOVT ACCESSION NO. DN687008	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 CEL BUILDING AND EXPERIMENTAL SUBGRADE COOLING SYSTEM, BARROW, ALASKA – Construction History and Performance Characteristics.		5. TYPE OF REPORT & PERIOD COVERED Final; Sep 1975 – Sep 1978
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 J. L. Barthelemy		8. CONTRACT OR GRANT NUMBER(s) 16 F52555
9. PERFORMING ORGANIZATION NAME AND ADDRESS CIVIL ENGINEERING LABORATORY Naval Construction Battalion Center Port Hueneme, California 93043		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62759N; 17 YF52555001/01.005
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Facilities Engineering Command Alexandria, Virginia 22332		12. REPORT DATE 11 April 1979
		13. NUMBER OF PAGES 56
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) 12 61p.		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

9 Final rept. Sep 75 - Sep 78,

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Permafrost subgrade cooling, Arctic building foundation, liquid convection cell application, cold region construction, construction materials, permafrost protection.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Gravel requirements for structures placed on unstable permafrost can be reduced by incorporating various insulation materials into the floor and foundation systems. However, to reduce the need for gravel even more, some means of extracting heat from the ground beneath the structure must be provided. During the summer of 1976, personnel from the Civil Engineering Laboratory erected a building on the ice-rich permafrost near Barrow, Alaska.

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20. Continued

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CEL BUILDING AND EXPERIMENTAL SUBGRADE COOLING SYSTEM, BARROW, ALASKA – Construction History and Performance Characteristics (final), by J. L. Barthelemy
TR-870 56 pp illus April 1979 Unclassified

1. Permafrost construction 2. Subgrade cooling I. YF 52.555.001.01.005

Gravel requirements for structures placed on unstable permafrost can be reduced by incorporating various insulation materials into the floor and foundation systems. However, to reduce the need for gravel even more, some means of extracting heat from the ground beneath the structure must be provided. During the summer of 1976, personnel from the Civil Engineering Laboratory erected a building on the ice-rich permafrost near Barrow, Alaska. The structure, placed on just 1 foot of gravel, has been used as a test bed to evaluate an experimental subgrade cooling system. The cooling system consists of 15 loop-configured heat exchangers called convection cells. During the winter months, heat losses from the building into the permafrost are redirected via these convection cells to the cold environment outside, thus preventing progressive degradation from thaw. To date, data collected from some 150 thermocouples located in the subgrade and heat-exchange systems have shown that the rate of winter heat removal is even greater than originally anticipated. Although a small cyclical displacement of the floor and foundation resulting from seasonal summer thaw and winter freezeback has been apparent, this movement is minimal compared to settlement which would have occurred had the massive ice present in the subgrade been allowed to thaw unchecked.

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INTRODUCTION

Presently, heated buildings on ice-rich or frost-susceptible frozen ground are usually constructed on thick pads of gravel or other stable soils, which act as a seasonal heat sink to preserve the frozen state of the underlying natural ground and thus ensure the integrity of the structure. Although lightly loaded structures are frequently elevated above the surface of the pad to provide an insulating air space, this is quite difficult to do with heavily loaded structures such as garages or aircraft hangars, which are, instead, usually built on thicker gravel pads. Well-designed combinations of structure and pad have proven highly reliable for construction on frozen ground. However, a problem becoming more apparent as development of the North continues is the scarcity of gravel in many areas, especially in the northern coastal plain of Alaska west of the Colville River (Ref 1). For coastal development, gravel has traditionally been mined from beaches, but in the vicinity of Barrow, for instance, this activity has seemingly accelerated beach erosion and shoreline regression and is currently not permitted (Ref 2). Inland from the coast, of course, transportation costs and logistics can make gravel a scarce commodity.

Gravel requirements for heated structures can be reduced by incorporating various insulation materials into the pad; however, to reduce this requirement further, it is necessary to provide some means of extracting heat from the ground below the structure. During the summer of 1976, a three-man field team from the Civil Engineering Laboratory (CEL), consisting of a mechanical engineer, a geologist, and an equipment specialist, erected a building on the permafrost near Barrow, Alaska. This building included an experimental system of natural convection heat exchangers called convection cells. The structure, placed on just 1 foot of gravel, has been used as a test bed to evaluate the potential for subgrade cooling of permafrost. A number of thermocouples were placed on the heat exchangers and in the ground so that temperature data could be monitored weekly throughout the year. In addition, a stable benchmark was placed near the building, and level measurements have been taken along the foundation and floor at the end of each summer and winter to detect seasonal heaving and settling.

The test structure, a nominal 54- by 40-foot ATCO "fold-a-way" building, was originally purchased for equipment cold storage and was, therefore, uninsulated. As a result, heat input into the ground is provided and controlled by a grid network of thermostatically controlled electric heat mats buried beneath the floor. The mats are divided into eight circuits on separate thermostats for more uniform maintenance of the desired temperature conditions across the floor area. The subgrade cooling system consists of 15 self-powered convection cells. Each convection cell is built as a loop and

consists of two connecting half-loop heat-exchange surfaces. The heat-intake half-loop is placed horizontally in the ground beneath the floor and joins the heat-rejection half-loop, which rises vertically outside the structure. Thus, so long as the ambient air temperature is lower than the ground temperature beneath the building, the liquid refrigerant naturally circulates around the convection cell. In this way, heat losses from the building into the permafrost are redirected via the heat exchangers to the cold ambient environment outside.

This report highlights the development and testing of the convection cell heat exchangers and erection of the building and subgrade cooling system at a test site within the compound of the Naval Arctic Research Laboratory (NARL). These topics are covered in detail in References 3, 4, 5, and 6. Greater detail is given to performance characteristics monitored from thermocouple and level data during the 2 years of operation.

The field monitoring program was originally envisioned as a 5-year effort, but lack of funds has necessitated its termination sooner than expected.

BACKGROUND

The concept of the self-regulated heat exchanger is not a new theme in polar regions. Two types of passive, one-way refrigeration devices have been used for nearly a decade in Alaska and Canada to stabilize piling in permafrost (Ref 7). Externally, the two are similar in appearance; however, internally one type operates using a single-phase, liquid-convection heat transfer while the other uses a two-phase, boiling-liquid and vapor-convection heat transfer. Historically, the liquid-convection and two-phase devices have been known in Alaska and Canada as the Balch and Long thermopiles, respectively, although more recently a number of variations, such as freezing cell (liquid convection), THERMO-TUBE (liquid convection), thermosiphon (two-phase) and Cryo-Anchor (two-phase) have been introduced. The Cryo-Anchor was developed by McDonnell Douglas Corporation to refrigerate the vertical support members on elevated sections of the Trans-Alaska pipeline.

In 1969, CEL began to investigate the potential use of passive refrigeration devices to accelerate the natural growth rate at the underside of an advancing ice sheet. Initially, both liquid-convection and two-phase cells were evaluated in cold chamber tests. However, it was decided early in the program to develop only the single-phase, liquid-convection model, which was subsequently named the freezing cell (Ref 8, 9). The Navy wanted a simple, compact heat exchanger that could be flown as conventional piping components to remote locations and then assembled, placed, and charged on-site by two or three men. Thus, operational requirements, rather than relative thermal efficiency or heat transfer potential, spearheaded development of the liquid-convection concept.

Investigations related to subsurface thickening of sea ice were completed in 1973; the gravel moratorium at Barrow was already in effect. Previously, CEL had purchased an uninsulated building for equipment cold storage at NARL. It was decided in early 1975 to use the freezing cells and building as a test bed for a subgrade cooling system.

CONVECTION CELL DEVELOPMENT

The freezing cell used for subsurface ice thickening was basically no more than a pipe, with a closed end positioned vertically in the ice sheet so that part was exposed to the cold air above and part to the warmer seawater below, as illustrated in Figure 1. The upper heat-rejection surface, called the cooling head, was fitted with fins to increase heat transfer. Liquid density differences generated within the cooling head and lower heat-intake pipe resulted in natural convection circulation. For modification to a subgrade cooling system, it was at first intended to slant the heat-intake pipes to a near-horizontal position under a building constructed at grade. However, cold chamber tests of slanted cells placed in freshwater cooled at 0C resulted in growth of a severely tapered ice shell (Ref 7). Obviously, the near-horizontal position of the heat-intake pipe caused a resistance to natural convection forces that virtually eliminated all circulation toward the bottom of the pipe.

It was thought that a loop-configured cell, where flow within the pipes is unidirectional rather than concentric, would result in a more uniform flow pattern and the problem of tapered ice growth would thereby be avoided. Figure 2 shows the basic idea behind the loop cell, although both the heating and cooling surfaces are pictured in a vertical plane. For modification to a subgrade cooling configuration, test loops were made by joining two 90-degree slant cells at top and bottom. In this way, the cooling head remained vertical while the heat-intake surface below was changed to a horizontal orientation.

Three generations of loop-configured convection cell followed, as described in Reference 7. The first generation loop was constructed using cooling heads claimed from old freezing cells used at Point Barrow to thicken sea ice, as shown in Figure 3. The cooling head of the loop consisted of two sections of 4-in.-diam steel pipe with fins, joined together at the top by a piece of 2-in.-diam pipe. Each upright had eight steel fins; each fin was 4.5 feet long, 4 inches deep, and 3/16 inch thick. However, since not enough reclaimed heads were available to build an entire subgrade cooling system, additional heat exchangers with increased fin area were manufactured.

Loops made from these improved heat exchangers were evaluated during the second generation tests. The cooling head maintained the same geometry, but this time each 4-in.-diam steel upright had 10 fins, each of which was 6 feet long, 2-1/2 inches deep, and 1/8 inch thick. Merely joining two 90-degree slant cells produced a balanced loop configuration. Thus, as the heated refrigerant left the heat-intake pipe and started to flow upwards, the cool-down action of the finned pipe actually counteracted and slowed down the flow rate. It wasn't until the liquid started down the second finned pipe that circulation was reinforced by heat rejection.

The third generation tests again used the improved cooling heads, but this time the heads were connected in parallel above one arm of the heat-intake half-loop. Both finned pipes were fed by a smaller unfinned pipe rising from the other arm of the heat-intake half-loop. Figure 4 shows the parallel heat exchanger and the nearly uniform ice growth that resulted. Figure 5 is a graphical comparison showing the history of the average working temperature

(measured at points along the outside surface of the heat-intake pipe) of the balanced, improved cooling head and the parallel, improved cooling head configurations. Not only did the latter operate at consistently colder temperatures, but the liquid flow rates, which were measured visually through a clear plastic section of 5-cm-diam pipe, doubled, reaching a maximum value of just under 10 cm/sec (Ref 7).

Thermal Performance

In order to design the subgrade cooling system and predict future performance, it was necessary to determine quantitatively the heat transfer characteristics of the convection cell. In the field installation, the rate at which heat is removed from the soil is related to the temperature of the buried heat-intake pipes. Since the convection cell heat exchanger is a thermal resistance device, the temperature of the heat-intake pipe is a function of air temperature and the total resistance to heat flow through the soil, through the convection cell, and from the cooling head to the surrounding air. In order to determine the overall heat-exchanger resistance (that is, combined liquid natural convection resistance within the piping and forced-air resistance from the cooling heat), the convection cell was tested as a freezing cell in 0C freshwater.

All cold chamber tests were conducted at continuous average air temperature and windspeed of -27C (-17F) and 1 m/sec, respectively. In this way, near steady-state conditions existed at each instant in time since heat capacity effects due to temperature adjustments within the growing ice mass and liquid refrigerant were very small compared to the overall heat transfer rate. In the steady-state approximation, the time-changing temperature of the heat-intake pipe is always some fraction of the ambient air temperature. Also, since water at the freezing point temperature produces concentric rings of ice around a cold pipe, the thermal resistance of the slowly growing ice shell is readily represented by basic heat transfer considerations. Thus, from Reference 10, one has the following relationship between heat-intake pipe temperature, air temperature, overall convection cell resistance, and ice shell resistance (thickness):

$$\theta = \frac{1}{1 + \left(\frac{2\pi k \ell}{\ln D}\right) R} \tag{1}$$

In Equation 1, the quantity of interest was the overall heat exchanger resistance, R. The thermal conductivity of ice, k, and the length of the heat-intake pipe, ℓ, were known. The pipe-to-air-temperature ratio, θ, was calculated from recorded thermocouple data. The outside-to-inside-diameter ratio, D, of the growing ice shell was measured physically at selected times during the test period.

Rearranging Equation 1 produces a relationship for R as a function of the temperature and thickness ratios:

$$R = \left(\frac{1 - \theta}{\theta}\right)\left(\frac{\ln D}{2\pi k \ell}\right) \tag{2}$$

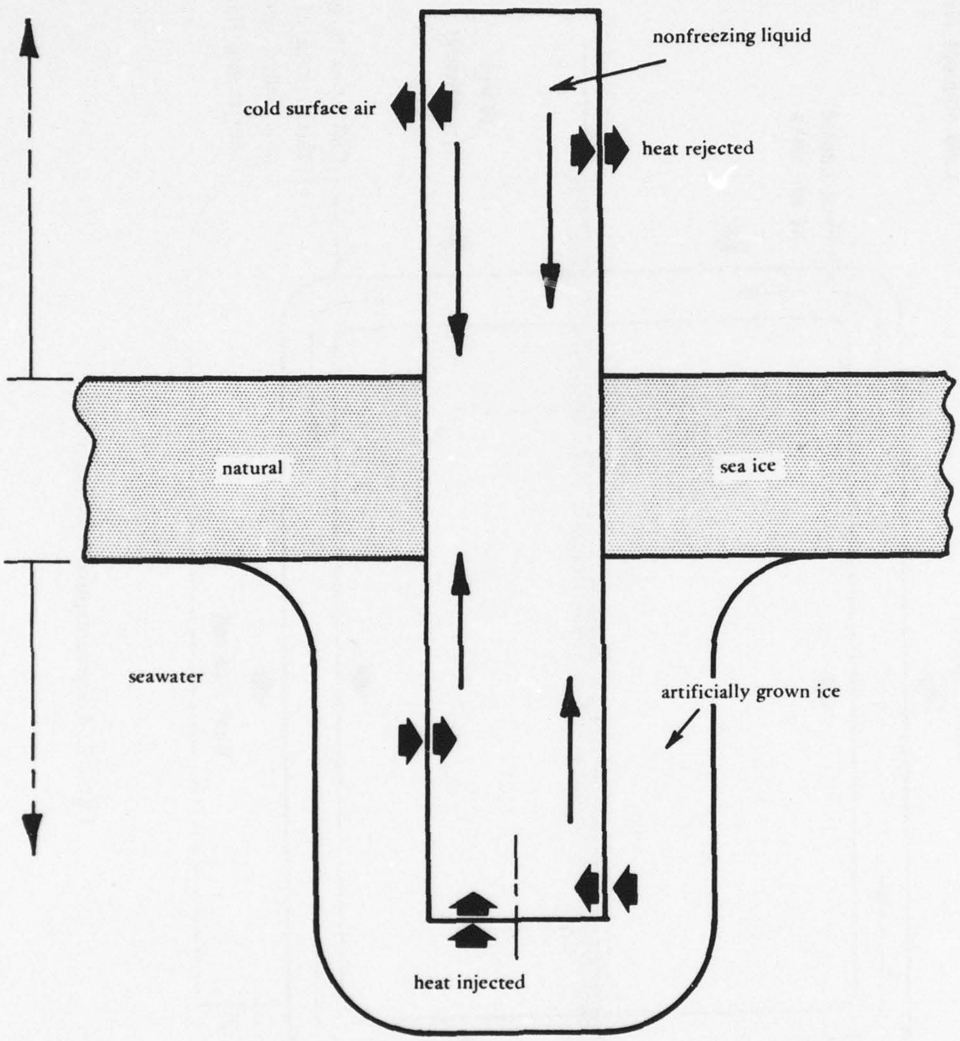


Figure 1. Liquid-convection ice-thickening device.

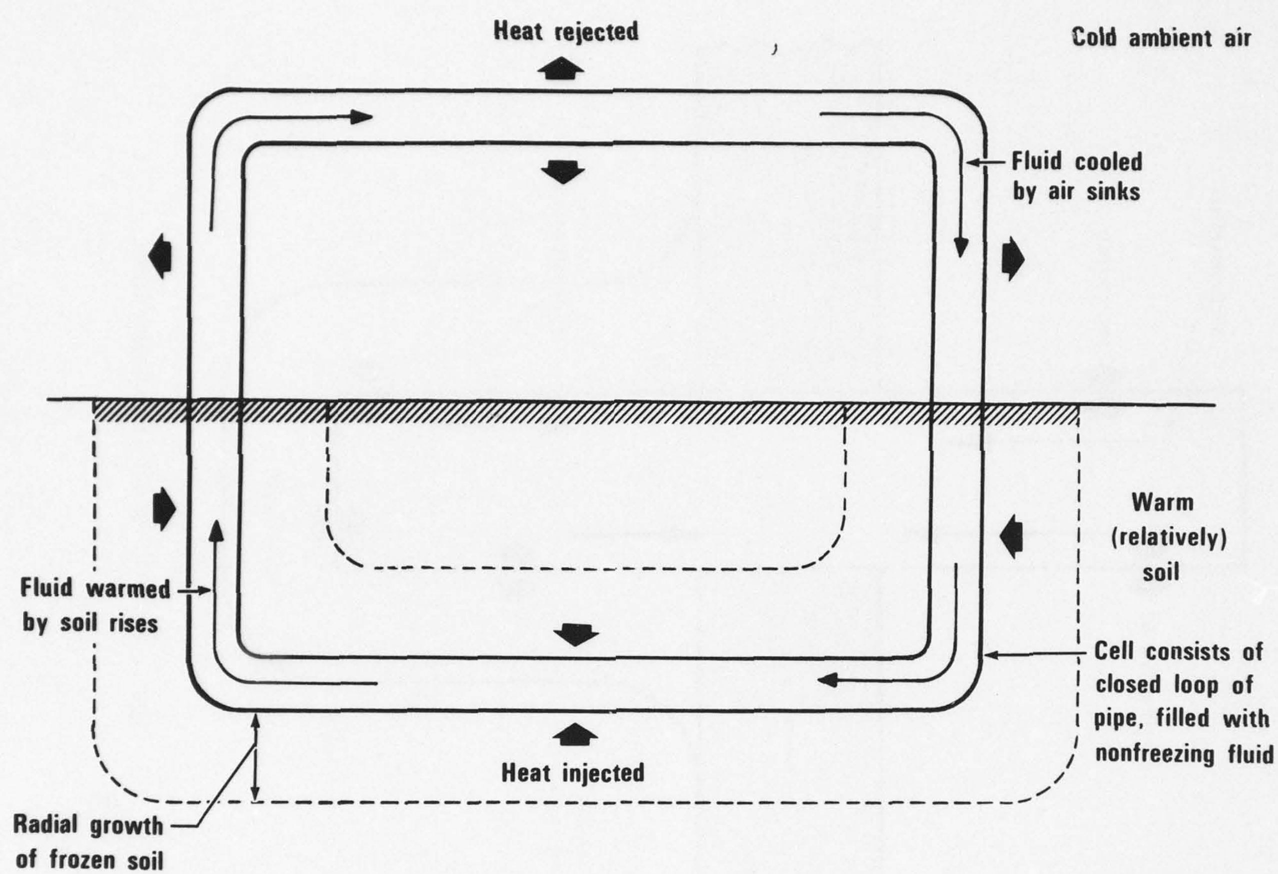


Figure 2. Loop-configured convection cell.

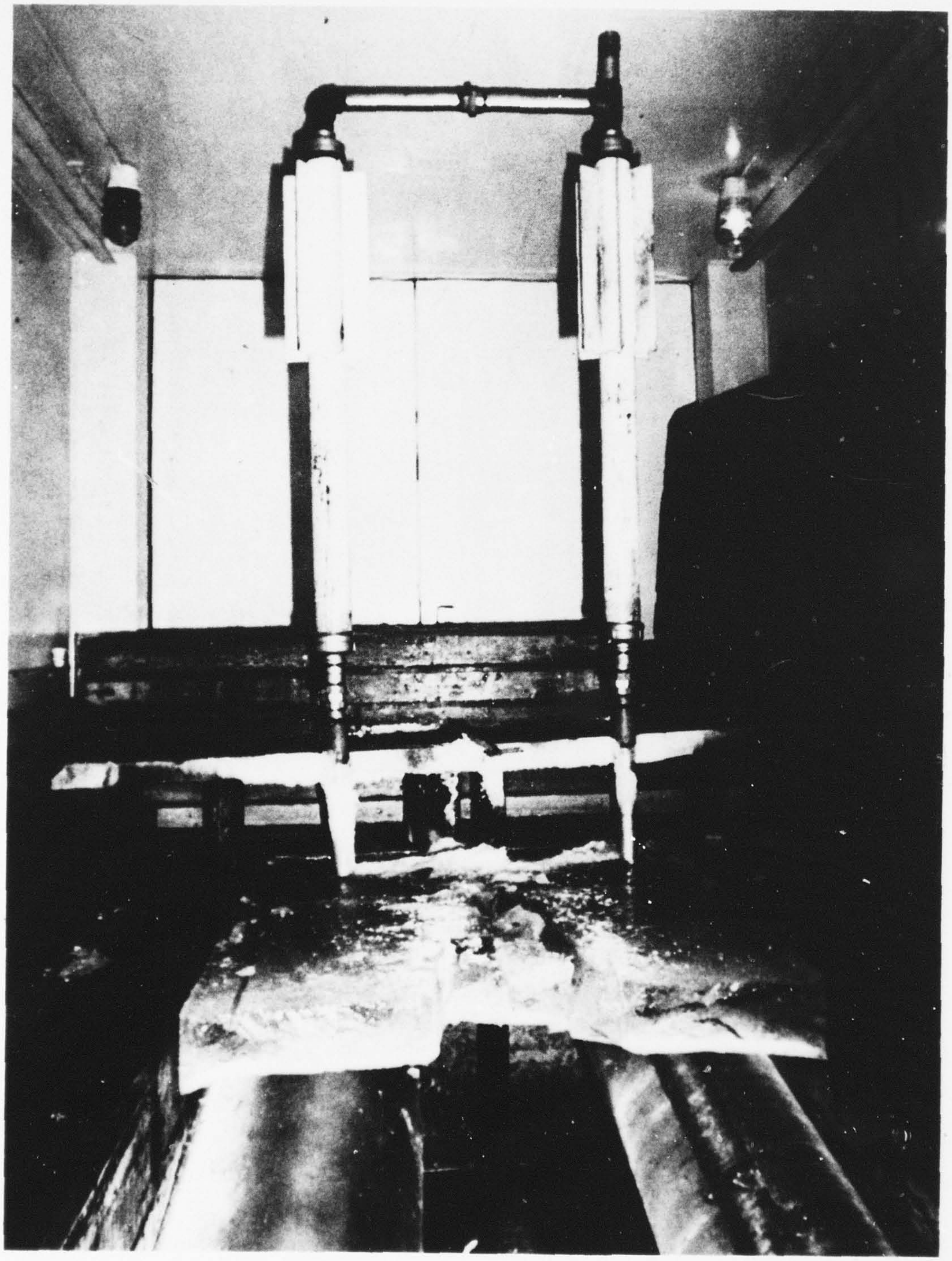


Figure 3. Ice growth around a convection cell of balanced cooling head design.

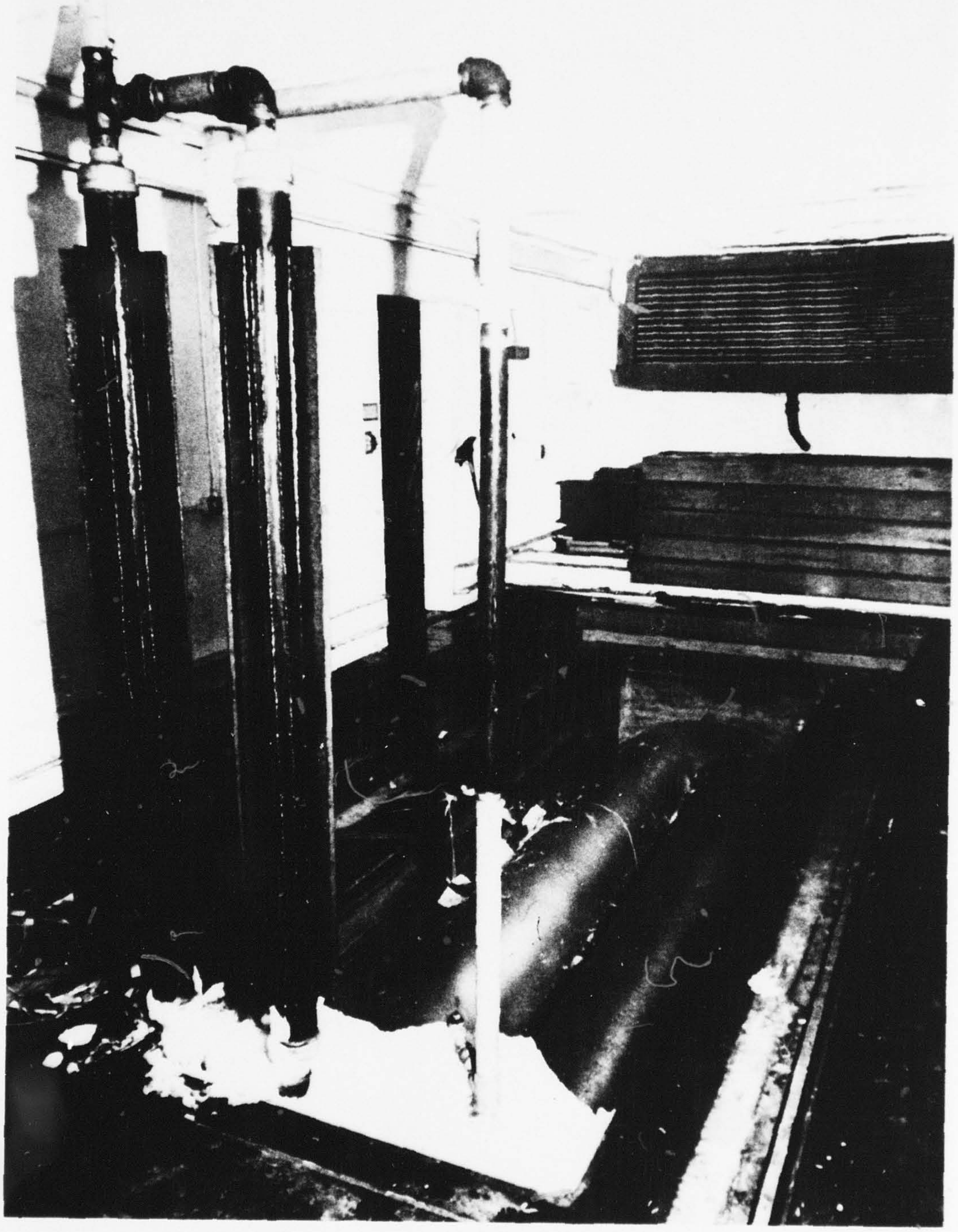


Figure 4. Ice growth around a convection cell of parallel cooling head design.

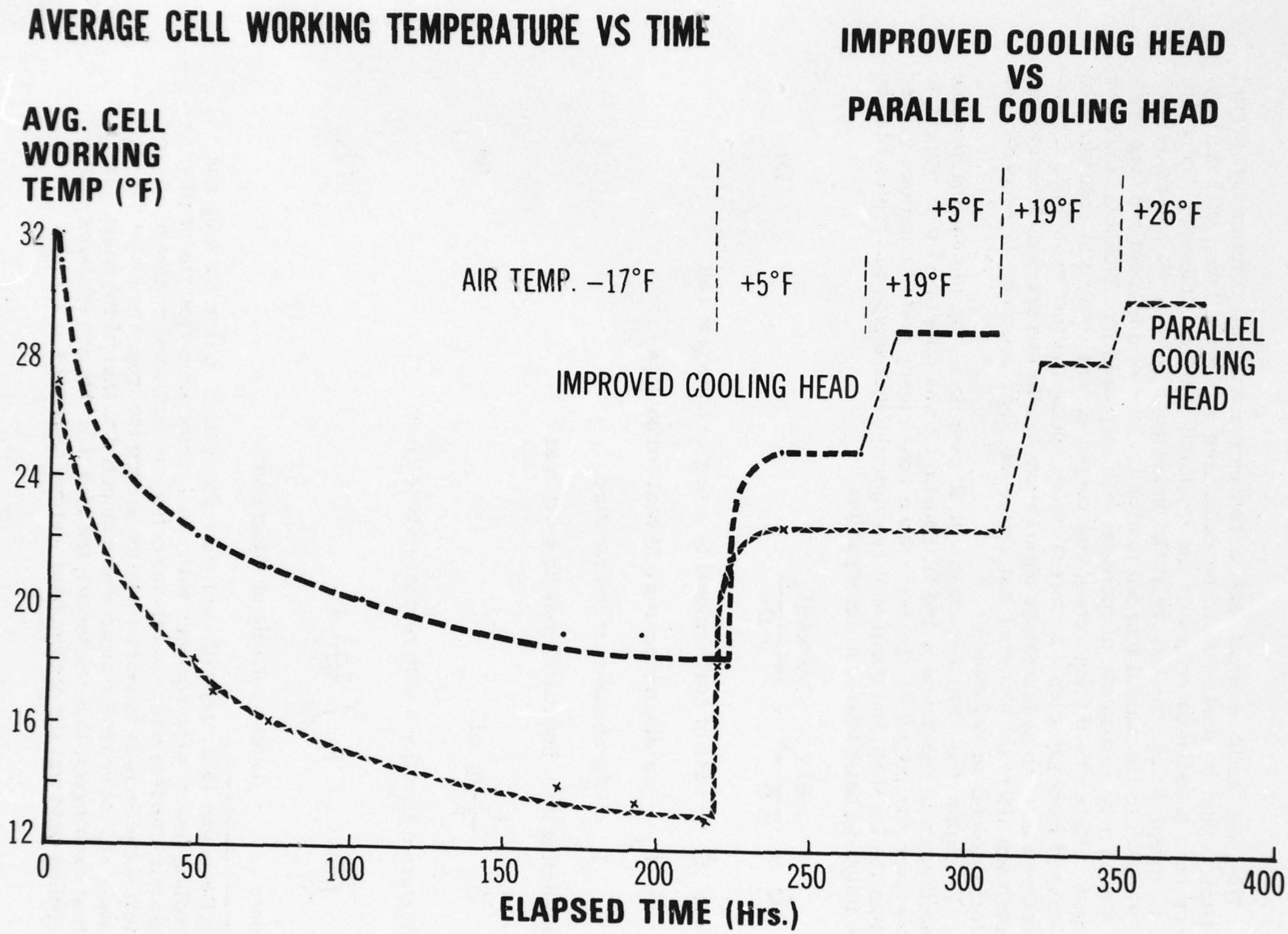


Figure 5. Thermal comparison of balanced and parallel cooling head configurations.

The "ice bath" method was a convenient way of determining overall resistance, and it allowed R to be calculated at various levels of heat input (since heat transfer decreases as the insulating ice shell thickens). There was some question as to the relative importance of the liquid-convection contribution to the overall thermal resistance. One would expect the magnitude of the internal resistance to increase with increased ice thickness, since the density differences driving convection decrease. Yet, the total resistance as calculated from Equation 2 at several times during the test maintained a near-constant value. Thus, laboratory observations reinforced previous freezing cell experience (Ref 8): internal natural-convection resistance is secondary to external forced-air resistance.*

To obtain the best assessment of R over time, by minimizing possible inaccuracies in measuring θ and D, Equation 2 was integrated with respect to time over the period of the test. Since near steady-state conditions existed within the ice shell, the transfer of heat into the intake pipe was represented by the following basic heat-transfer equation:

$$\dot{Q} = \frac{-2\pi k \ell T_p}{\ln D} = \frac{-2\pi k \ell \theta T_a}{\ln D} \qquad (3)$$

where $\dot{Q}$ = rate of heat removal by a single convection cell

T_p = surface temperature of heat-intake pipe

T_a = the ambient air temperature

Eliminating ln D, Equation 2 may be written as

$$\dot{Q} = \frac{T_a}{R}(\theta - 1) \qquad (4)$$

Integrating Equation 4 with respect to time gives

$$\int_o^t \dot{Q}\, d\tau = T_a \int_o^t \frac{\theta - 1}{R}\, d\tau \qquad (5)$$

where τ = dummy variable of integration

---

*In December 1977, three of the fifteen convection cells in the subgrade cooling system were equipped with small submersible-type pumps (that did not interfere with natural convection circulation when turned off) to test the effects of forced circulation around the loop. The long-term result was a <1C lower temperature when compared to that of the unassisted heat exchangers, thus reinforcing the idea that the air-resistance of the cooling head was the predominant thermal resistance.

The left-hand integral (LHI) is simply the latent heat of energy of the volume of ice produced during the test period (since heat-capacity effects are small and, therefore, may be neglected):

$$LHI = \frac{\pi d_i^2}{4} (D^2 - 1) \ell \rho L \qquad (6)$$

where d_i = inside diameter of ice shell around a heat-intake pipe

ρ = density of ice

L = latent heat of fusion of ice

Since R was already said to be nearly constant (for the given laboratory conditions), it can be removed from the right-hand integral (RHI):

$$RHI = \frac{T_a}{R} \int_0^t (\theta - 1)\, d\tau \qquad (7)$$

The remaining right-hand integral in θ is evaluated graphically after first plotting a curve using recorded thermocouple data. After rearranging Equations 6 and 7, the resulting Equation 8 is used to calculate R.

$$R = \frac{4T_a}{\pi d_i^2 (D^2 - 1) \ell \rho L} \int_0^t (\theta - 1)\, d\tau \qquad (8)$$

Final Design

The value of R calculated under test conditions for the parallel arrangement of improved cooling heads was 0.028C/W. However, the final convection-cell cooling head design was somewhat different. Rather than build two types of heat exchanger cooling head - one pairing two old cooling heads and a second pairing two improved cooling heads - it was decided to mix them. Thus, the convection cell cooling heads installed at Barrow consist of one old-type finned pipe in parallel with one new-type finned pipe. In addition, a shorter horizontal section of finned pipe was used as crossover to feed the parallel arrangement, as shown in Figure 6.

The thermal resistance of the cooling head is sensitive to prevailing wind conditions. Preliminary heat-transfer calculations assumed an average windspeed of 20 km/hr (12.5 mph) for the Barrow area during the winter season. With this average windspeed and the change in heat-transfer area between the convection cell tested in the cold chamber and that actually assembled for the subgrade cooling experiment, a design R value of 0.012C/W (0.0064 F-hr/Btu) was used in predicting expected freezeback characteristics.

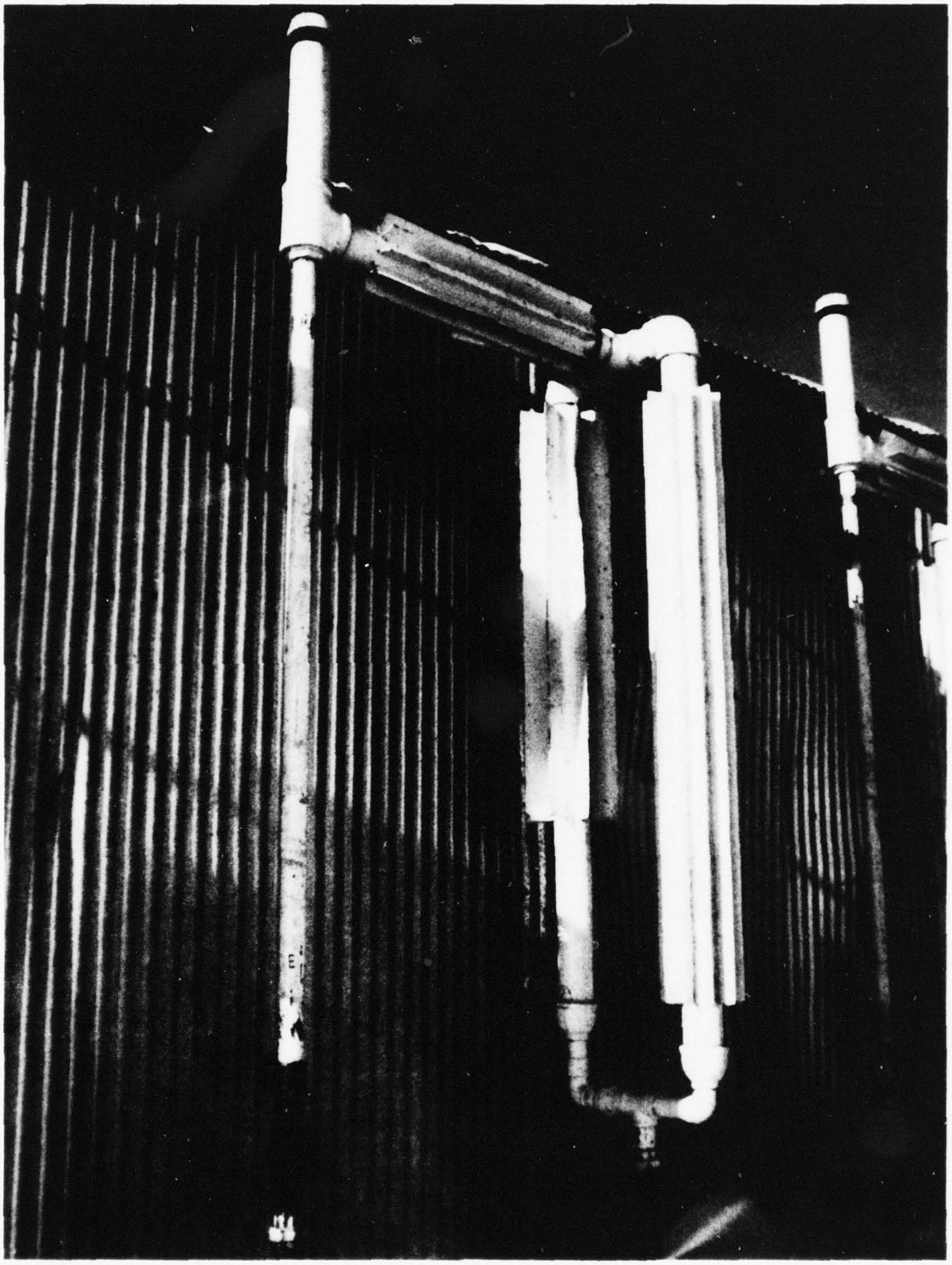


Figure 6. Cooling head configuration as built at Barrow, Alaska.

The buried heat-intake half loops consist of two standard 21-foot lengths of 2-in.-diam steel pipe connected by a shorter 4-foot section of pipe. Figure 7 shows in plan the position of the heat-intake pipes beneath the floor of the building.

BUILDING AND BUILDING SITE

The ATCO "fold-a-way" building is a steel-framed, 40-foot wide structure consisting of prefabricated roof/wall modules, each of which is 9 feet in length. Each module is identical and is made up of four panels, two for the side walls and two for the gabled roof. Three hinged joints (at the eaves and the top of the roof) allow the panels to be fastened together at the factory and folded into a compact stack for shipment; they can then be easily unfolded and erected at the construction site. Any number of modules can be joined to become, with the addition of endwalls, a completed building.

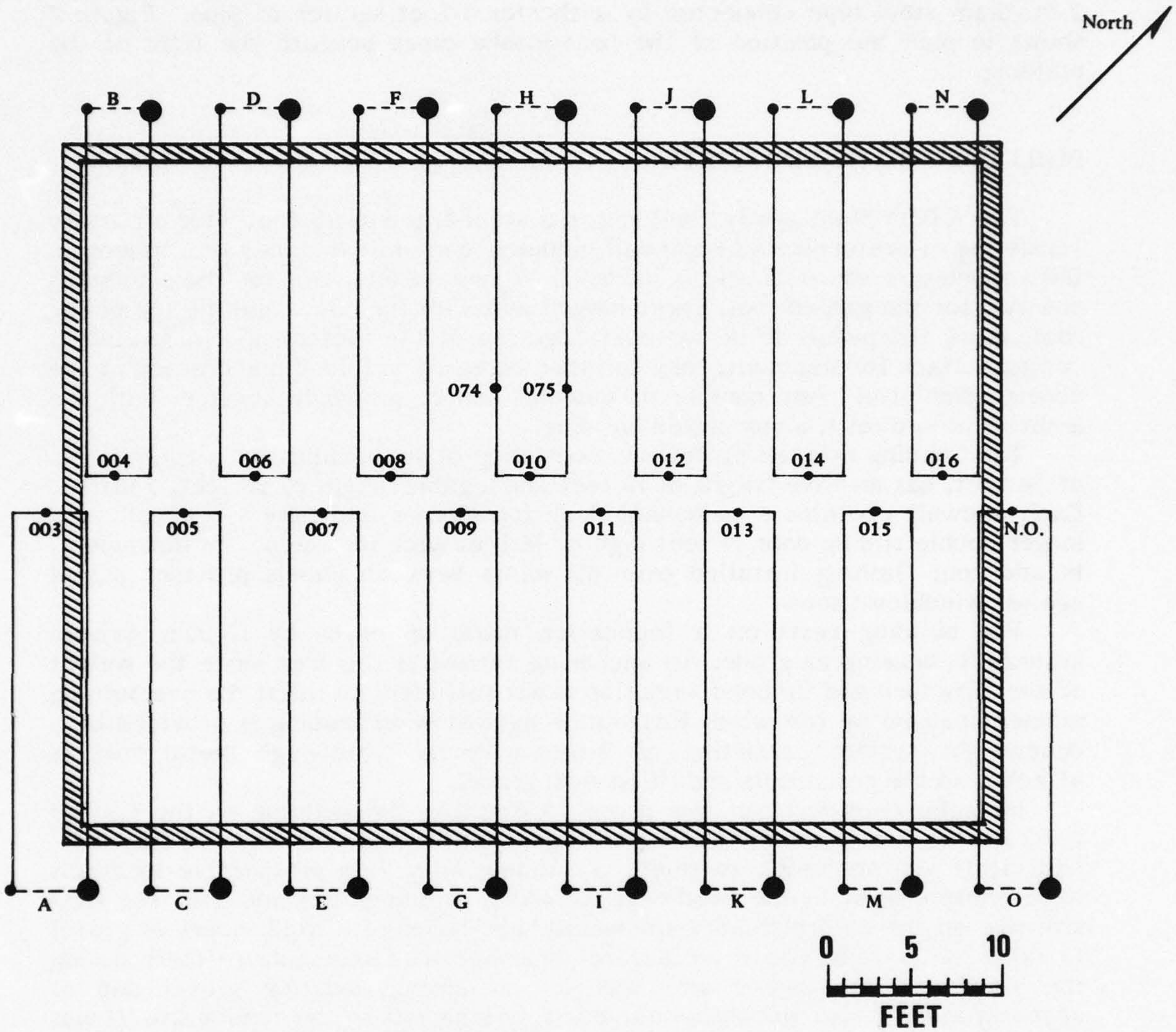
The building erected at Barrow, consisting of six modules for a total length of 54 feet, has an eave height of 14 feet and a gable height of 20 feet, 5 inches. Each endwall contains a personnel door for ingress and egress, as well as a larger double sliding door 14 feet high by 16 feet wide for equipment movement. In addition, flashing installed over all joints between panels provides a seal against windblown snow.

The building rests on a foundation made up of 4- by 12-inch wooden groundsills bearing at grade. An anchoring system is required since the weight of the structure and timber foundation is not sufficient to resist the overturning moment caused by the wind. Resistance against wind loading is provided by a deadweight system consisting of 2-foot-wide by 1-foot-high metal troughs attached to the groundsills and filled with gravel.

Initially, consideration was given to erecting the building on the natural tundra after first placement of a gravel pad of minimum thickness. In July 1975, CEL staff visited NARL to select a building site. Two prospective locations were chosen, both to the southeast of NARL Buildings 553 and 554. The first site was on the natural tundra and would have required 6 to 12 inches of gravel to raise the building above melt-water drainage that accumulates there during the summer. The second site was on an already-existing gravel pad of approximately 2-foot thickness, immediately adjacent to the tundra site. It was felt that logistically it would be advantageous to remove some of the gravel from the pad, rather than place the required gravel on the tundra, thus the decision was made to erect the structure on the already existing gravel pad.

During April 1976, a subsurface geological study was performed at the selected building site. The results of that investigation were documented in Reference 3. In summary, the surficial soils were found to be organic silts with a moisture content averaging 170%, and densities ranging from 60 to 80 lb/cu ft (960 to 1280 kg/m^3). Massive clear ground ice was found in many locations from a depth of 1-1/2 to 5 feet below the tundra surface and was presumed to be the result of intersecting ice wedges.* It was thought that this site, with its high ice content soils, would certainly provide a good "worst case" test of the subgrade cooling concept.

*This was later confirmed by the excavation of several test pits in the area prior to erecting the building.



NOTES: (1) All thermocouples on this page were assembled from standard limit thermocouple wire and attached by hose clamps to the top of each freeze pipe (all of which are at a depth of approximately 2-½ feet below the zero datum).
(2) Numbers refer to channel numbers on data-logger output.
(3) Letters are permanent designations of convection cell loops.
(4) Heavy circle on each convection cell loop denotes the side with the two vertical heat exchangers; i.e., the "cold" side.
(5) N.O. of cell O means "not operating."

Figure 7. Plan view of heat-intake half-loops beneath the building.

GROUND HEATING SYSTEM

The experiment was designed to test the effectiveness of loop-configured convection cells in preserving the frozen condition beneath a heated building constructed at grade on permafrost. Since the ATCO structure is not insulated and need not be heated in its function as equipment storage, it was decided to simulate heat input into the ground by means of thermostatically controlled heat mats buried in the floor. The units selected are powered by 208 volts AC and produce a heat output density of 16 W/sq ft. Each mat consists of a single resistance wire that is looped back and forth along the length to form a parallel network of wires with 3-inch spacings. All heating elements are 36 inches wide; however, five different lengths (5-1/2, 11, 22, 33, and 44 feet) were used to guarantee a complete coverage of floor area without overlap. Also, it was necessary to combine shorter mats with longer ones on individual circuits so as not to exceed the 22-ampere rating for a single thermostat. One final consideration was used in designing the layout heat mats. Since areas nearer the walls of the building "see" the cold ground outside, it was thought best to control peripheral mats on the same circuit; thus, the arrangement of basically concentric circuits shown in Figure 8 was planned. The mats as installed are divided into eight circuits, each on a separate thermostat for better maintenance of conditions across the floor areas. Actually, two remote-sensing thermostats (each with a 1-1/2F operating temperature differential) wired in series were used for each circuit. One was set to a slightly higher temperature than the other (for backup, should the primary unit fail).

To minimize the upward loss of heat from the mats to the inside of the cold building, 2,000 sq ft of 2-in.-thick rigid foam insulation was purchased and shipped to the construction site. The insulation selected was Dow Chemical HD-300 Styrofoam with a thermal conductivity of 0.2 Btu-in./hr-sq ft-F.

BUILDING ERECTION

Erection of the ATCO "fold-a-way" structure by the three-man CEL field team began in early Aug 1976, shortly after the arrival of the summer resupply "Cool Barge" at Barrow, and was completed before the onset of subfreezing air temperatures in late September. The overall construction effort consisted of a number of identifiable phases which are summarized in this section.

Site Preparation

Plans called for burial of the heat-intake pipes in trenches cut 1-1/2 feet into the tundra. It was necessary to remove the 2-foot overlay of gravel down to the tundra surface prior to excavating in order to prevent sloughing of material into the trenches. The gravel was removed and stockpiled (using the CEL Low Ground Pressure D-4 tractor) until the exposed surface was primarily organic silt. The site after clearing was checked for level, and the perimeter was found to be within 2 inches of level, with the center depressed about 4 inches below the average perimeter elevation. The tundra surface around the site was

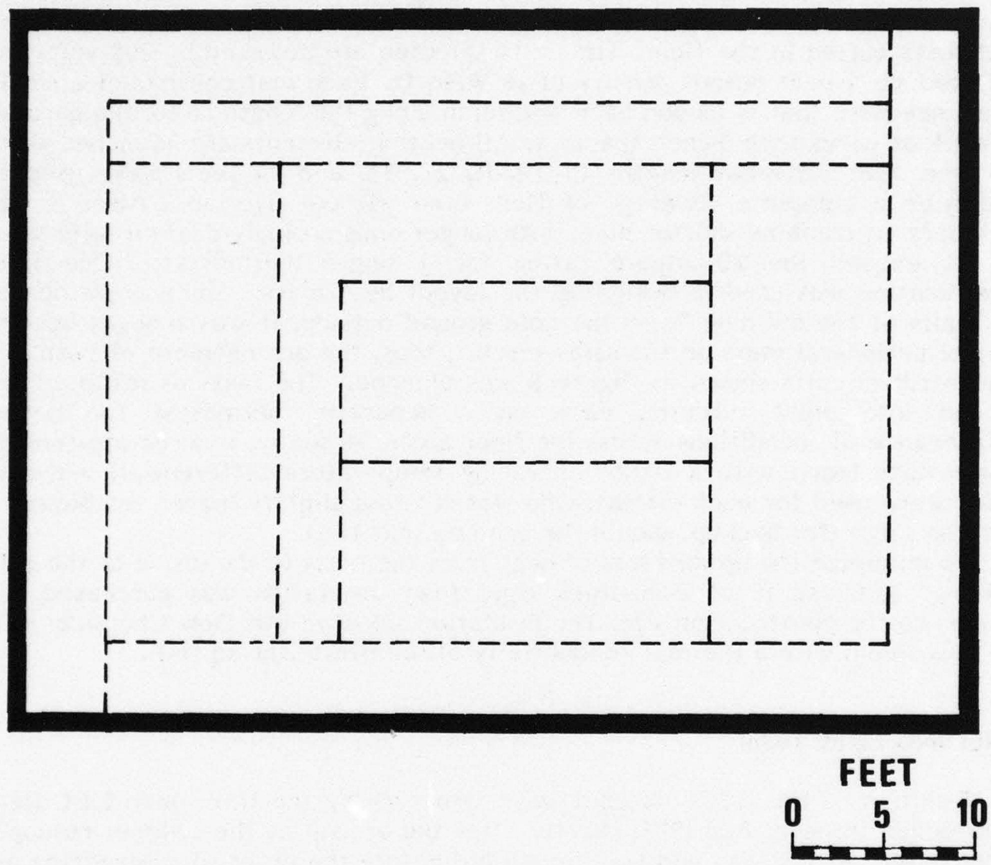


Figure 8. Arrangement of heat-mat circuits.

surveyed and found to be typically about 8 inches above the average elevation of the cleared building site. Since the water level on the tundra was at or near the surface, this meant that the entire site after clearing was below water level.

It was anticipated that drainage into the trenches would be a problem. Immediately after the site was cleared of gravel, trenches 8 inches wide by approximately 2 feet were dug (using the CEL trencher) along the southeast and southwest borders, adjacent to the tundra. A small sump was excavated at the intersection of the two trenches and was pumped out as required by a small gasoline-powered centrifugal trash pump. However, during excavation of the trenches for the heat-intake pipes, water continued to drain onto the site from the gravel pad, and additional water was generated in place by the melting of ice within the trenched permafrost. The site became progressively wetter, muddier, and more difficult to work in (as shown in Figure 9).

Excavation and Placement of Heat-Intake Pipes

Plans called for placing convection cells 4 feet apart and staggered on opposite sides of the building. Thus, a total of 15 cells was required for complete coverage (see Figure 7). They were installed so as to orient the building with its long axis at an angle of 45 degrees to the prevailing snow-carrying winds. This was desirable from the standpoint of minimizing drift accumulation. Since the prevailing wind is basically from the east, there were actually two choices of orientation: (1) northeast/southwest (parallel to the coastline and perpendicular to most other buildings at NARL); and (2) northwest/southeast (perpendicular to the coast and parallel to most buildings). The first orientation was chosen since it was thought that in that configuration those cooling heads receiving greater exposure to the sun (solar heating) because of their facing more south would also be in a better position to receive more exposure from prevailing winds (chill cooling). In addition, the upwind door of the building, which should remain more free of snow, would be in a more useful location with the first orientation.

The CEL trencher (Davis Model TF-700) was used to excavate the 8-inch-wide trenches for the below-ground, heat-intake half-loops. This ladder-type trencher was equipped with the factory short boom, and standard Kennametal, Inc., Model C-1 carbide-tipped cutting teeth. Since the target depth for the pipes was 1-1/2 feet below the tundra surface, the cuts were made to a slightly greater depth. The upper foot of excavated material was already thawed, and the frozen soil beneath was about 50% high ice content organic silt and 50% clear ice (probably the top of ice wedges). The clear ice did not present any clearly defined pattern across the site, reinforcing the theory of several generations of intersecting ice wedges. In any case, the amount of ice beneath the building site was found to be substantial, as was the potential for settlement. Although the material itself was not difficult to excavate, slow rates of trenching were necessary to ensure a straight cut of uniform depth.

Trenches were dug one at a time to minimize thawing. After each pre-assembled half loop was lowered into position, the trench was backfilled with excavated material. The backfill was placed in thin 4- to 6-inch lifts and

Figure 9. Illustration showing the muddy condition at the excavation site.

compacted by project personnel walking in the trench. Particular care was taken to insure that material was worked in beneath the pipes. Some trenches had to be pumped prior to backfilling because of excessive drain-water accumulation. In addition, where clear ice had been excavated from the trench, it had to be used in the backfill since it was already mixed with the soil and no alternative source of fine-grained backfill was available. As this ice thawed, it compounded the saturation problem. In general, then, the backfill around and above the heat-intake pipes consisted of saturated or oversaturated soils.

Following the emplacement of all 15 half loops, the surface of the site was back-bladed with the D-4 tractor to an approximately level grade. Gravel which had previously been cleared and stockpiled was then replaced on the site to an elevation approximately 1 foot above the average elevation before excavation. String lines were set to establish foundation grade and to align the 4- by 12-inch wooden groundsill foundation. The gravel beneath the timbers was trimmed or filled to exact grade prior to permanent placement. The foundation on the northeasterly end of the building was not installed at this time so that the crane would not have to maneuver over and possibly damage the foundation while placing the building sections.

Panel Erection

The individual module sections were unfolded and placed, using a crawler-type crane with a 50-foot boom. A smaller crane or "cherry picker" could have been used, but it was decided that this particular machine would be easier to use, given the soft ground conditions at the site. A crew of six (including the CEL team, but not including the crane operator) was used, and the operation progressed smoothly, considering that none of the group had ever erected a building of this type before (or even seen one being erected). Figures 10 and 11 show the unfolding and placement of a typical building panel. As each panel was unfolded and lifted onto the wooden groundsill, it was aligned, secured by lag screw to the foundation, and bolted to the adjacent section. The crew of six was large enough to allow this bolting to take place while the next panel was being unfolded. Minor problems were encountered in aligning bolt holes between adjoining panels, and some torch cutting of new holes was required. Following erection of the six building sections, the southwesterly endwall was placed using the small more maneuverable cherry picker. After the structure was fully erected, flashing was installed over all joints between panels; and, although this was a time-consuming and often frustrating job, no major problems were encountered.

The simple deadweight system used to anchor the building against wind loading was installed last. Troughs 8 feet long by 2 feet wide by 1 foot high were fabricated from 4- by 8-foot sheets of 12-gauge steel. These were assembled into a continuous trough along both sides of the building, bearing at the same grade as the groundsills, and attached to the groundsill by lag screw. The troughs were filled level with gravel; density was about 100 lb/cu ft.

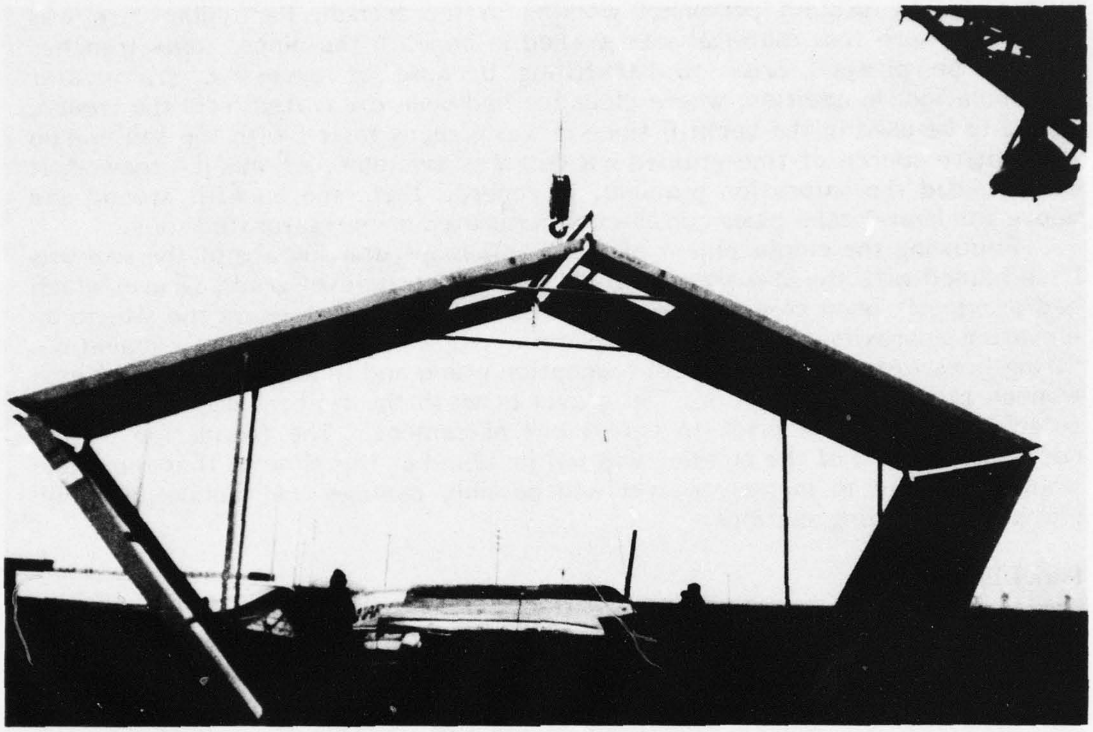


Figure 10. Unfolding of a "fold-a-way" building section.

Floor System

The electrically traced heat mats were placed down at what is herein defined as floor grade ("zero" elevation) - that is, on the 1 foot of gravel covering the natural tundra. The mats were covered by the 2-inch-thick panels of styrofoam, with a 6-inch layer of gravel in between for thermal protection. The insulation in turn was covered by another 12-inch thickness of gravel as protection against vehicle traffic inside the building. Figures 12 and 13 show a small skip loader placing gravel on the mats and the insulation, respectively. Figure 14 shows a cross section through the subgrade beneath the building. As a final procedure, pierced steel runway material (Marston matting) was placed down as a floor to prevent rutting of the gravel. Figure 15 shows the completed floor structure within the building.

It should be kept in mind by the reader that the building simulates a heated structure bearing on only 1 foot of gravel. Floor grade is therefore defined as the level of the heat mats. The additional gravel and foam insulation above were included only to limit upward heat loss and provide structural protection.

Figure 11. Adjoining two sections.

Figure 12. Placing gravel over the heat mats.

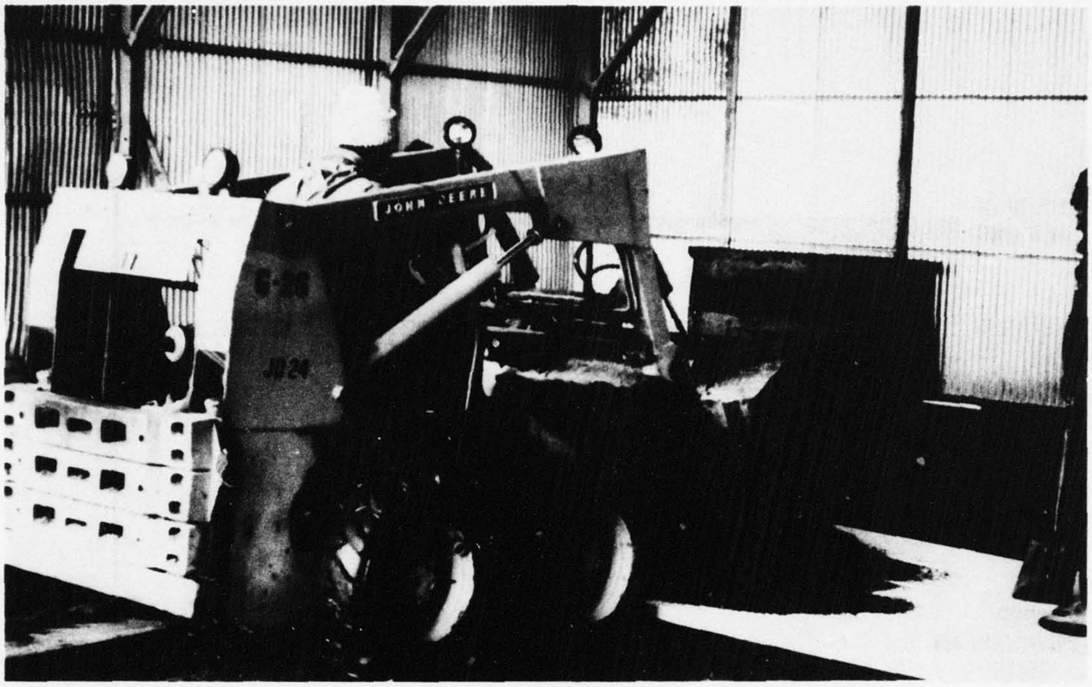


Figure 13. Placing gravel over the insulation.

Cooling Head Installation

The above-ground heat exchangers - the cooling heads - were constructed from standard black iron pipe and fittings and were painted with a zinc chromate primer and a white enamel topcoat to minimize heat input from solar radiation. They were assembled totally at NARL within the confines of a heated building. Although the parallel arrangement of heat-exchange piping was superior from the standpoint of heat transfer, this configuration was difficult to assemble because of differences in thread engagement and misalignment of threads. However, all of the cooling heads were completed and tested for leaks prior to installation.

The cooling heads were positioned (using a cherry picker) on risers from the heat-intake half loops. One side of each head, near the top, was anchored back to the wall of the building to prevent oscillation in the wind. To do this, a short piece of steel angle stock was placed through a hole cut in the corrugated metal skin of the building and welded to the pipe girt, and the other end attached to the cooling head with a large U-bolt. After the heads were braced, the cells were filled with a 50% mix (by volume) of ethylene glycol and water. Each cell holds approximately 23 gallons of refrigerant. A number of minor leaks appeared, but none were serious enough to worry about at the time. They were repaired during a return trip to NARL during November 1976. Figure 16 shows the outside of the completed structure, including the cooling head portions of the convection cells.

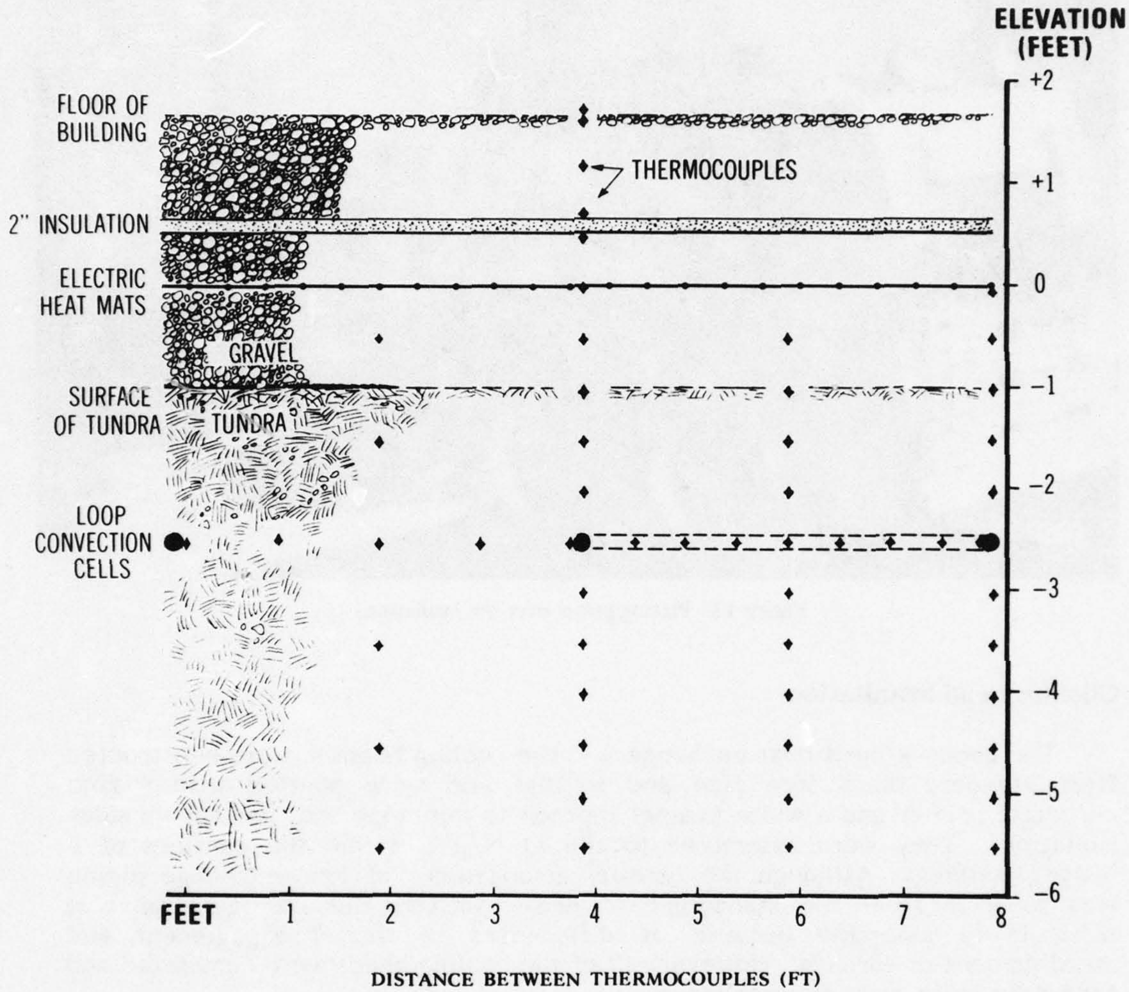


Figure 14. Cross section through the subgrade.

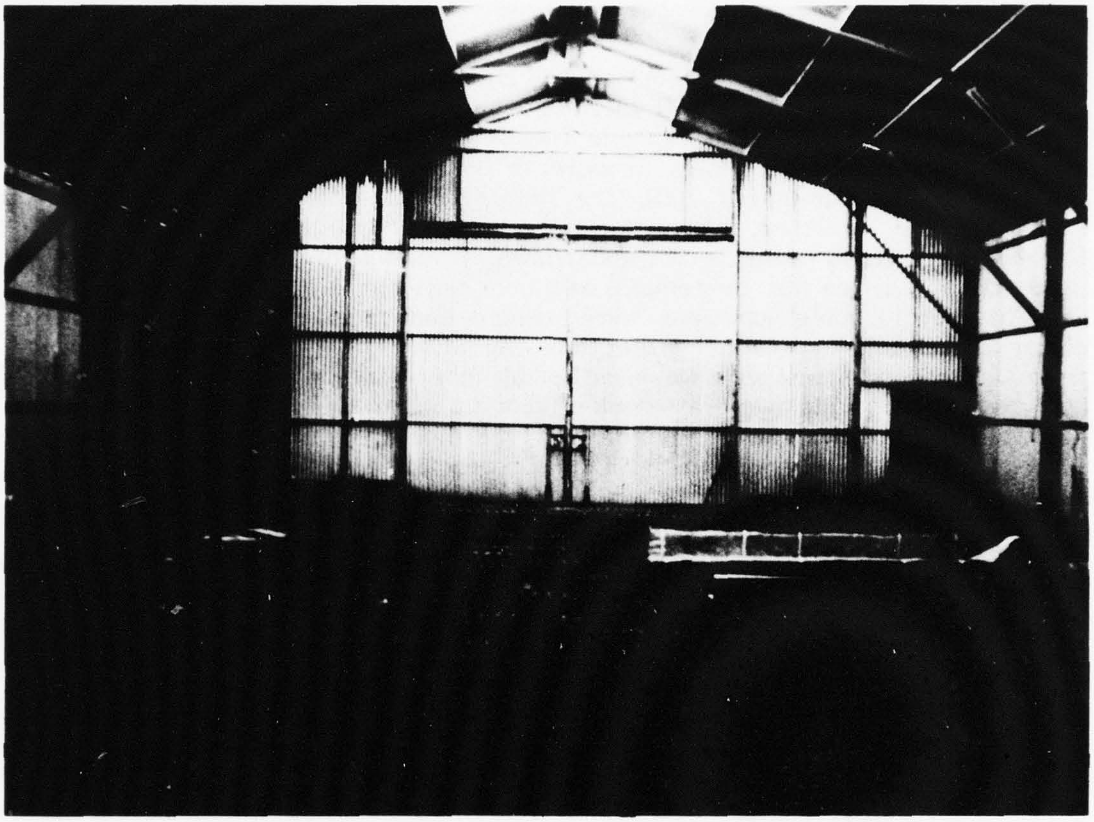


Figure 15. Completed Marston Matting floor.

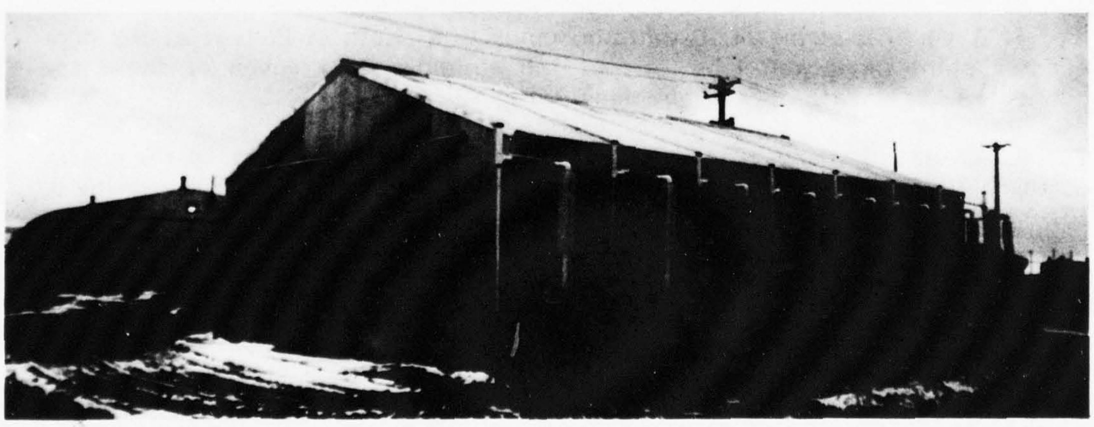


Figure 16. View of completed building.

Instrumentation

To monitor changes in convection-cell and subgrade temperature, a number of copper-constantan (type "T") thermocouples were connected to a DigiTec Model 1590 Datalogging Thermocouple Thermometer with a DigiTec Model 635-3 Scan Expander (which serves to increase the data input capability from 20 channels to a maximum of 200). The recording instrument was placed in a specially made, insulated, thermostatically controlled box that is heated by four 100-watt light bulbs connected in series/parallel for longer life. Two small fans inside the box insure that air remains at a near-uniform temperature.

All thermocouple junctions were welded and then potted in epoxy for electrical insulation and protection against corrosion. Twenty-gauge thermocouple extension wire was used for all junctions and lead-ins. About one-half the thermocouples were assembled from standard limit wire, and the other half from special limit wire. Four random thermocouples of each type of wire were calibrated in an ice bath to develop correction factors for the particular batch lots. It was determined that the correction factor for the standard limit wire is -0.5C and that for the special limit wire is -0.6C.

At the time that the building was erected in 1976, 137 copper-constantan thermocouples were installed beneath the building. Of those, 120 were connected to the datalogger.* Table 1 shows the conversion from thermocouple number to datalogger input terminal number. The thermocouples were located as follows:

1. One thermocouple on the crossover pipe of each convection cell heat-intake pipe to monitor convection cell performance. The thermocouple on cell O, apparently damaged during installation, could not be reached for repair and did not provide data (see Figure 7).

2. A vertical string of 15 thermocouples to a depth of 29 feet in the natural ground away from the building. Only 11 of these are connected to the datalogger (see string 1, Figure 17).

3. A vertical string of 10 thermocouples to a depth of 19 feet at the one-quarter point along the long axis of the building. Only seven of these are connected to the datalogger (see string 2, Figure 17).

4. A vertical string of 15 thermocouples to a depth of 29 feet at the center of the building. Only 11 of these are connected to the datalogger (see string 3, Figure 17).

5. A vertical string of 10 thermocouples to a depth of 19 feet at the one-quarter point along the short axis of the building. Only seven of these are connected to the datalogger (see string 4, Figure 17).

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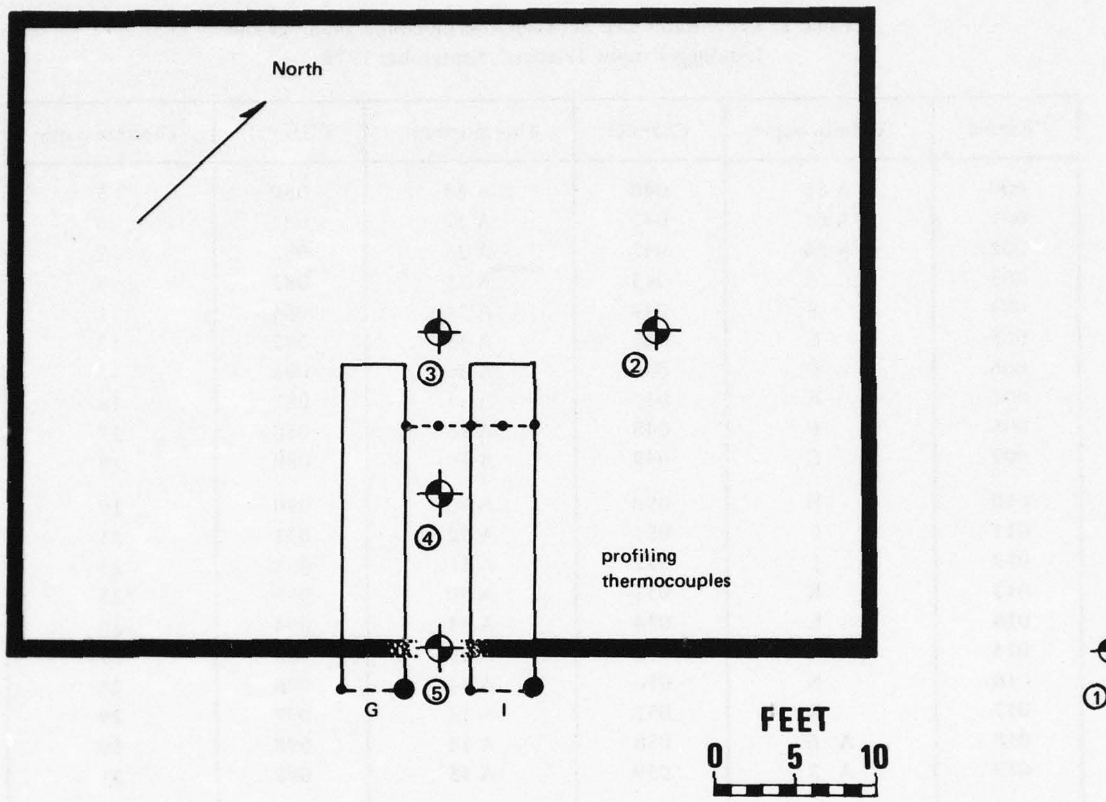
*The Scan Expander houses cards which contain 10 input terminals each. Initially only 12 cards were purchased and inserted into the Expander.

Table 1. Cross Reference Between Thermocouple Number and Datalogger Input Terminal, September 1976.

Channel	Thermocouple	Channel	Thermocouple	Channel	Thermocouple
000	A 65	040	A 28	080	5
001	A 64	041	A 27	081	6
002	A 66	042	A 26	082	7
003	A	043	A 25	083	9
004	B	044	A 24	084	11
005	C	045	A 35	085	13
006	D	046	A 36	086	15
007	E	047	A 37	087	16
008	F	048	A 38	088	17
009	G	049	A 39	089	18
010	H	050	A 40	090	19
011	I	051	A 52	091	21
012	J	052	A 51	092	23
013	K	053	A 50	093	25
014	L	054	A 53	094	26
015	M	055	A 55	095	27
016	N	056	A 54	096	28
017	R	057	A 13	097	29
018	A 6	058	A 14	098	30
019	A 5	059	A 15	099	31
020	A 4	060	A 16	100	32
021	A 3	061	A 17	101	34
022	A 2	062	A 18	102	36
023	A 1	063	A 19	103	38
024	A 7	064	A 20	104	40
025	A 8	065	A 21	105	41
026	A 9	066	A 22	106	42
027	A 10	067	A 23	107	43
028	A 11	068	A 41	108	44
029	A 12	069	A 42	109	46
030	A 47	070	A 43	110	48
031	A 48	071	A 44	111	50
032	A 49	072	A 45	112	51
033	Q	073	A 46	113	52
034	A 34	074	U	114	53
035	A 33	075	T	115	54
036	A 32	076	1	116	55
037	A 31	077	2	117	56
038	A 30	078	3	118	58
039	A 29	079	4	119	60



String 1		String 2		String 3		String 4		String 5	
1′	076	1′	087	1′	094	1′	105	0′	112
3′	077	3′	088	3′	095	3′	106	2′	113
5′	078	5′	089	5′	096	5′	107	4′	114
7′	079	7′	090	7′	097	7′	108	6′	115
9′	080	11′	091	9′	098	11′	109	8′	116
11′	081	15′	092	11′	099	15′	110	10′	117
13′	082	19′	093	13′	100	19′	111	14′	118
17′	083			17′	101			18′	119
21′	084			21′	102				
25′	085			25′	103				
29′	086			29′	104				

NOTES:
(1) All thermocouples on this page were assembled from standard limit thermocouple wire.
(2) Numbers refer to channel numbers on datalogger output (e.g., string 1, 076, 077, etc.)
(3) Letters are permanent designations of convection cell loops.
(4) Channels shown are referenced to depth in feet below zero datum, which is taken as foundation grade of the building; i.e., 1 foot above the tundra surface.
(5) String 5 is located just outside the building foundation and is covered by deadweight trough filled with 1 foot of gravel.

Figure 17. Location of vertical thermocouple strings.

6. A vertical string of 10 thermocouples to a depth of 18 feet under the edge of the building on the short axis. Only eight of these are connected to the datalogger (see string 5, Figure 17).

7. A profiling network of 57 thermocouples at various horizontal and vertical positions around two convection cells (cells I and G) (see Figure 18).

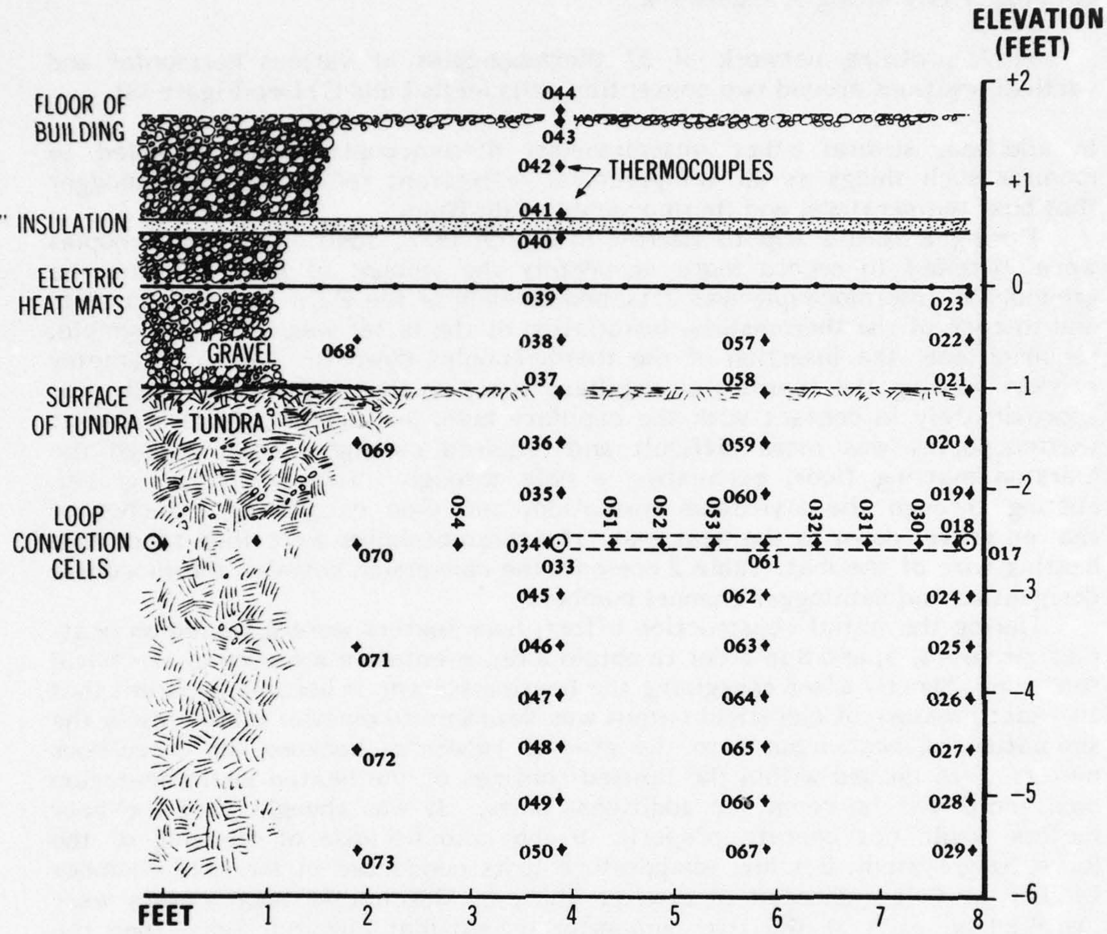
In addition, several other miscellaneous thermocouples were installed to monitor such things as air temperature, refrigerant temperature, datalogger "hot box" temperature, and thermocouple calibration.

During a return trip to Barrow in March 1977, additional thermocouples were installed to record more accurately the amount of heat entering the ground. One thermocouple was attached to each of the eight heat-mat circuits and to each of the thermostats. Installation of the latter was relatively simple, requiring only the insertion of the thermocouples down the 1-1/2-in.-diameter conduit housing the thermostat capillary tube, so that the thermocouple was approximately in contact with the capillary bulb. Installation of the heat-mat thermocouples was more difficult and required cutting a hole through the Marston matting floor, excavating a hole through 1 foot of frozen gravel, cutting through the styrofoam insulation, and then excavating 6 inches of thawed gravel down to the heat mat. The thermocouples were then taped to a heating wire of the mat. Table 2 presents the conversion between thermocouple designation and datalogger channel number.

During the initial construction effort, hour meters were installed on heat-mat circuits 1, 5, and 8 in order to obtain a representative measure of electrical "on" time. Shortly after energizing the heating system, it became apparent that an exact measure of electrical output was desirable to monitor more closely the simulation of heat input into the ground. However, because the three-hour meters were housed within the limited confines of the heated instrumentation box, there was no room for additional units. It was thought that the hour meters would not operate properly in the cold because of freezing of the lubricating system, but low temperature tests conducted in the cold chamber facility at CEL indicated otherwise. Thus, in March 1977 hour meters were installed on each of the five unmonitored heat-mat circuits. Since then the weighted average for the entire electrical heating system as well as individual outputs for each of the separate eight circuits have been calculated.

To monitor any elevation changes of the building resulting from heaving or settling, a permanent benchmark was installed in the frozen ground in the vicinity of the building. Following recommendations contained in Reference 11, the benchmark consists of a 21-foot length of 2-inch-diam pipe (with a flange at the bottom) frozen into the ground. The upper 10 feet of the pipe is surrounded by a 6-inch pipe casing, and the annulus filled with a grease to prevent the transmission of heaving forces to the benchmark.*

*The grease is a mixture by weight of 85% Texaco "Almag" oil and 15% paraffin wax procured under National Stock Number 9160-00-285-2047.



NOTES: (1) All thermocouples on this page were assembled from special limit thermocouple wire.
(2) Numbers refer to channel numbers on datalogger output.
(3) Following thermocouples not shown:
000 = outside air temperature
001 = hot box temperature
002 = calibration junction (at present will read air temperature inside building)
(4) Thermocouples 033 and 017 were internal.

Figure 18. Network of profiling thermocouples.

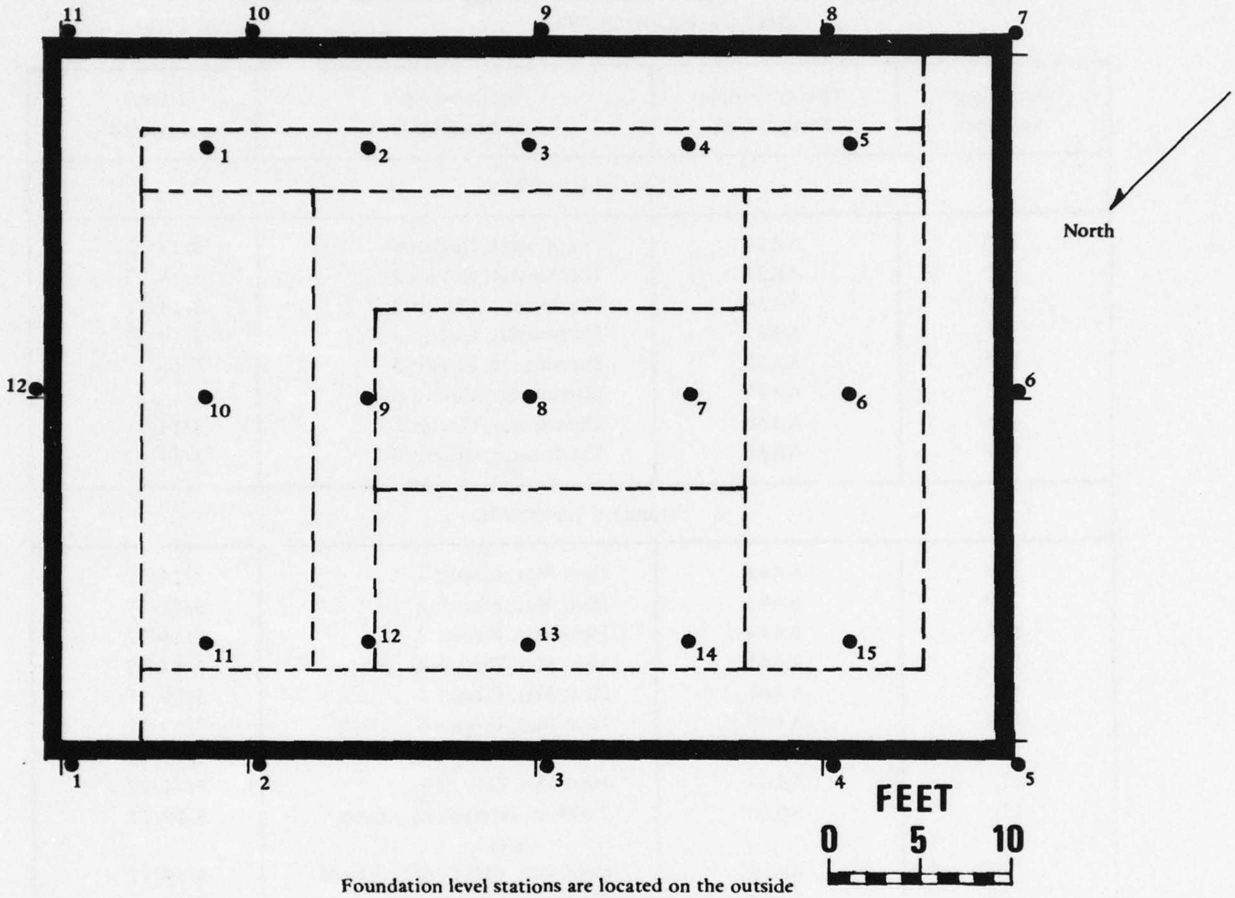
Table 2. Cross Reference Between Datalogger and Thermocouples Added During March 1977.

Datalogger Channel	Thermocouple Designation	Thermocouple Location	Date Connected
Special Limit Wire			
120	AA34	Thermostat, Circuit 1	3/14/77
121	AA35	Thermostat, Circuit 2	3/14/77
122	AA36	Thermostat, Circuit 3	3/14/77
123	AA37	Thermostat, Circuit 4	3/14/77
124	AA38	Thermostat, Circuit 5	3/14/77
125	AA39	Thermostat, Circuit 6	3/14/77
126	AA40	Thermostat, Circuit 7	3/14/77
127	AA41	Thermostat, Circuit 8	3/14/77
Standard Limit Wire			
128	AA42	Heat Mat, Circuit 1	3/14/77
129	AA43	Heat Mat, Circuit 2	3/14/77
130	AA44	Heat Mat, Circuit 3	3/14/77
131	AA45	Heat Mat, Circuit 4	3/14/77
132	AA46	Heat Mat, Circuit 5	3/19/77
133	AA47	Heat Mat, Circuit 6	3/19/77
134	AA48	Heat Mat, Circuit 7	3/14/77
135	AA49	Heat Mat, Circuit 8	3/14/77
136	AA50	1-1/4 in. Horizontally from AA47	3/19/77
137	AA51	Cold arm, Cell I cooling head	3/19/77
138	AA52	Warm arm, Cell I cooling head	3/19/77

Foundation level stations were located on the outside edge of the wooden groundsill foundation around the perimeter of the building. In addition, floor level stations were marked at various points on the protective Marston matting inside the building. The location of all level stations is shown in Figure 19. Level readings are taken near the end of each summer and winter season, whenever CEL personnel are at NARL.

HEAT TRANSFER MODEL

The convection cell operates as a heat exchanger only during those periods when air temperatures around the cooling head are lower than ground temperature around the heat-intake pipe. The overall yearly effect is a seasonal summer melt beneath the building, followed by a seasonal winter freezeback.



Foundation level stations are located on the outside edge of the wooden groundsill on the appropriate side of each joint as depicted by the lines perpendicular to the foundation.

Floor level stations are located at the intersection of imaginary lines drawn through the outer endwall joints and the section joints.

Figure 19. Location of level stations on foundation and floor.

Preliminary calculations indicated that a building with no insulation in the floor could not be simulated. The degree-days of heating throughout the entire year would be greater than the degree-days of cooling available during just the winter months. It was decided to simulate a floor condition whereby maximum summer thaw would not penetrate to a depth greater than 2 feet below floor grade - that is, 6 inches above the heat-intake pipes. This requirement was thought necessary to guarantee the structural integrity of the heat exchangers.

A trial-and-error approach was employed, with the following assumptions made: (1) the convection cells operate during the 7 coldest months and do not operate during the 5 warmest; (2) the simulated air temperature inside the "heated" building is a constant 68F (20C); (3) seasonal thaw begins each summer at the gravel/tundra interface; and (4) the subgrade can be represented by an average soil condition. Regarding this last assumption, results from the previously mentioned geological study (Ref 3), as well as earlier work conducted in the area by Paige (Ref 12), were used to generate a "typical" soil condition. Actually, a wide variety of soil structures were encountered at the site.

The Modified Berggren Equation was used to determine maximum expected penetration of the "active layer" during the 5 months of convection cell inactivity (Ref 11). Evaluation of that equation indicated that a building placed on a 1-foot-thick gravel pad and heated to 68F would require a floor containing the equivalent of a 2-inch thickness of foam-type insulation (thermal conductivity of 0.2 Btu-in./sq ft-hr-F). For such a structure, the summer thaw penetration would be approximately 1 foot beneath the tundra/gravel interface. Thus, the thermostats were set to simulate this condition.

PERFORMANCE

The convection cells were charged in late September 1976 with a liquid refrigerant consisting of 50% water and 50% ethylene glycol by weight. For the next 2 months, the heat exchangers were allowed to refreeze the thawed fill material in the trenches around the heat-intake pipes. The electric heat-mat circuits were energized in early December 1976. The 1-foot-thick gravel pad above the tundra thawed within the first week, and after three weeks the upper 6 inches of tundra was thawed in some places. The thaw front stabilized at a depth of 6 to 12 inches below the tundra surface, depending on the location with respect to the cold heat-intake pipes.

The static position of the thaw front was at a depth greater than that expected. Thermocouple data showed that temperatures recorded at the capillary bulb were greater than the thermostat setting, thus excessive heat was entering the ground. The 56F temperature recorded at "floor" grade (zero elevation) more closely modeled a building heated to 68F with no insulation in the floor, rather than a building with 2 inches of foam-type insulation.

A thermostat similar to those used in the subgrade cooling system was tested in the cold chamber facility at CEL. It was found that calibration was sensitive to the prevailing air temperature (the thermostats were placed exposed in the cold building). It was therefore necessary to individually reset each of the units at Barrow. This operation was completed in early April 1977,

and during the remainder of the month the thaw zone retreated to a position near the interface between gravel and tundra.

Figure 20 shows the progression of the thaw front during the 1977 summer season. Maximum summer thaw extended to a depth just below the 2 feet predicted by modified Berggren calculations. Figure 21 shows the freezeback pattern recorded during the 1977/78 winter season. Freezeback to the gravel/tundra interface was nearly complete by the beginning of March.

Heat Removal (Ref. 13)

When a convection cell is tested at constant air temperature and wind speed in 0C (32F) freshwater, the surface temperature of the heat-intake pipe decreases slowly as ice thickness increases. For this near steady-state situation, the ratio of intake pipe temperature to air temperature, θ, becomes a good means of establishing and comparing heat-exchanger efficiency. For illustration, it can be assumed that the ice shell can be maintained at some static thickness.* Then θ will assume a constant steady-state magnitude. If the air temperature is suddenly subjected to a step change (without accompanying growth or decay of ice), the same value of θ will be established - but only after some period of time. During the interim, heat-exchanger temperatures (and thus θ) are influenced by the thermal capacitance of the ice shell and (to a lesser degree) the liquid refrigerant. Under these transient conditions, the usefulness of θ as an indication of convection cell performance is greatly diminished.

For example, if a convection cell with fixed ice shell thickness is suddenly exposed to a constant warmer air temperature, temperatures within the heat exchanger (depending upon the thermal capacity of the ice mass) will be kept at a lower-than-steady-state level for some time due to the cooling effect of the ice. Thus, during the transient period, θ will be "artificially" high. If the cell is exposed to some fluctuating air temperature, which is the situation under field conditions, it becomes even more difficult to determine just what the steady-state θ should be.

The same problem is true of the subgrade cooling installation where thermal capacity is built into the frozen soil mass. Simply looking at the ratio of pipe-to-air temperature at isolated points in time is largely meaningless because of thermal lag. However, the "true" value of θ can be isolated by measuring both the intake-pipe and air temperatures at regular intervals over a period of time. Figures 22 and 23 show 48-hour recordings of θ, based upon 1-hour increments of pipe and air temperatures. Windspeed in 3-hour increments is included for reference. It should be noted that the pipe temperature used to generate θ represents the average pipe temperature of the 13 convection cells located totally beneath the building. The two end cells were excluded from the averaging process. Figures 24 and 25 show temperature profiles around the heavily instrumented convection cell at the start of the December and March test periods, respectively.

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*In theory, the ice shell should continue to grow indefinitely in 0C freshwater, as long as the heat-intake pipe is maintained below the freezing point temperature.

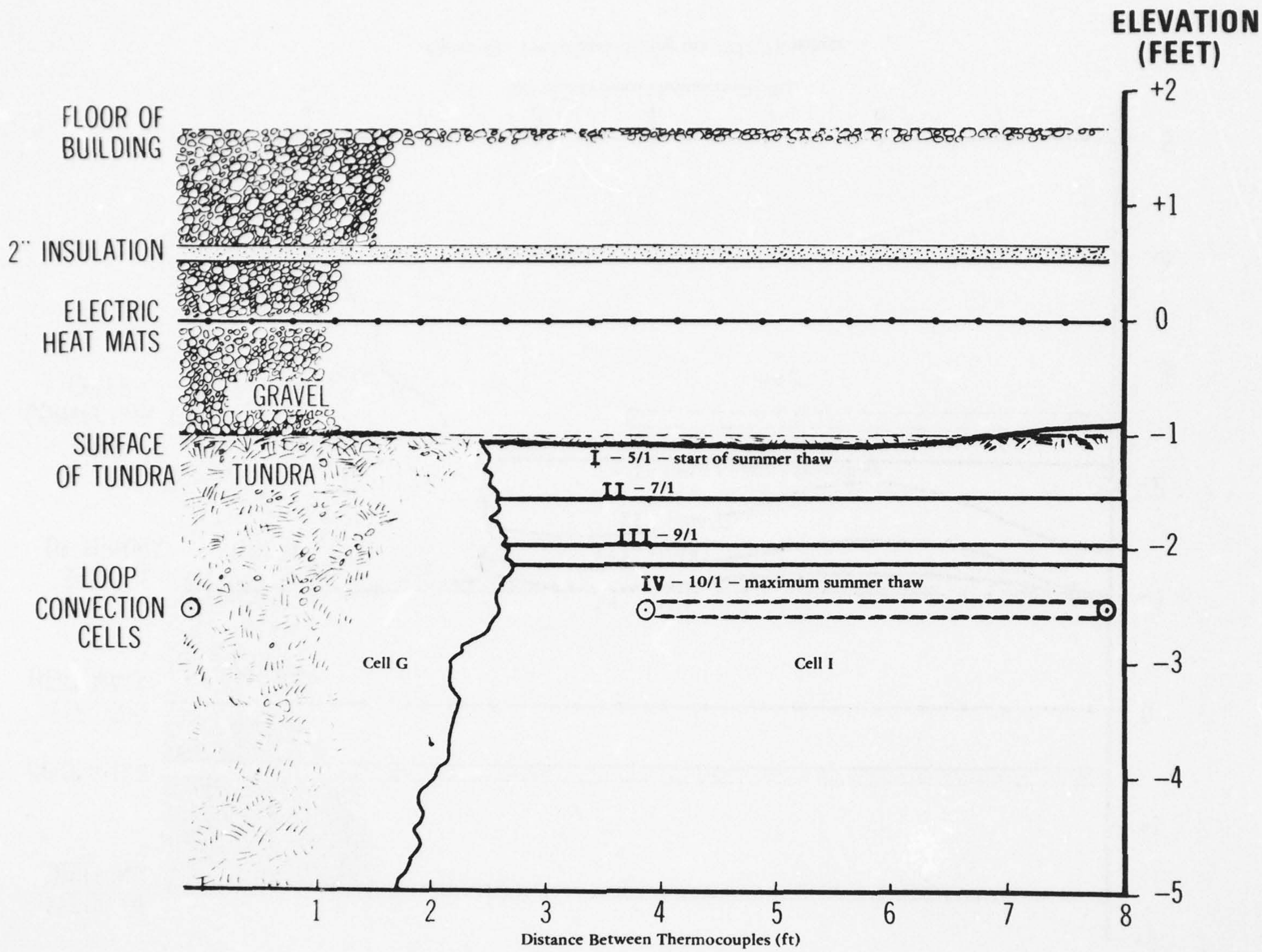

Figure 20. Thaw front progression during the 1977 summer.

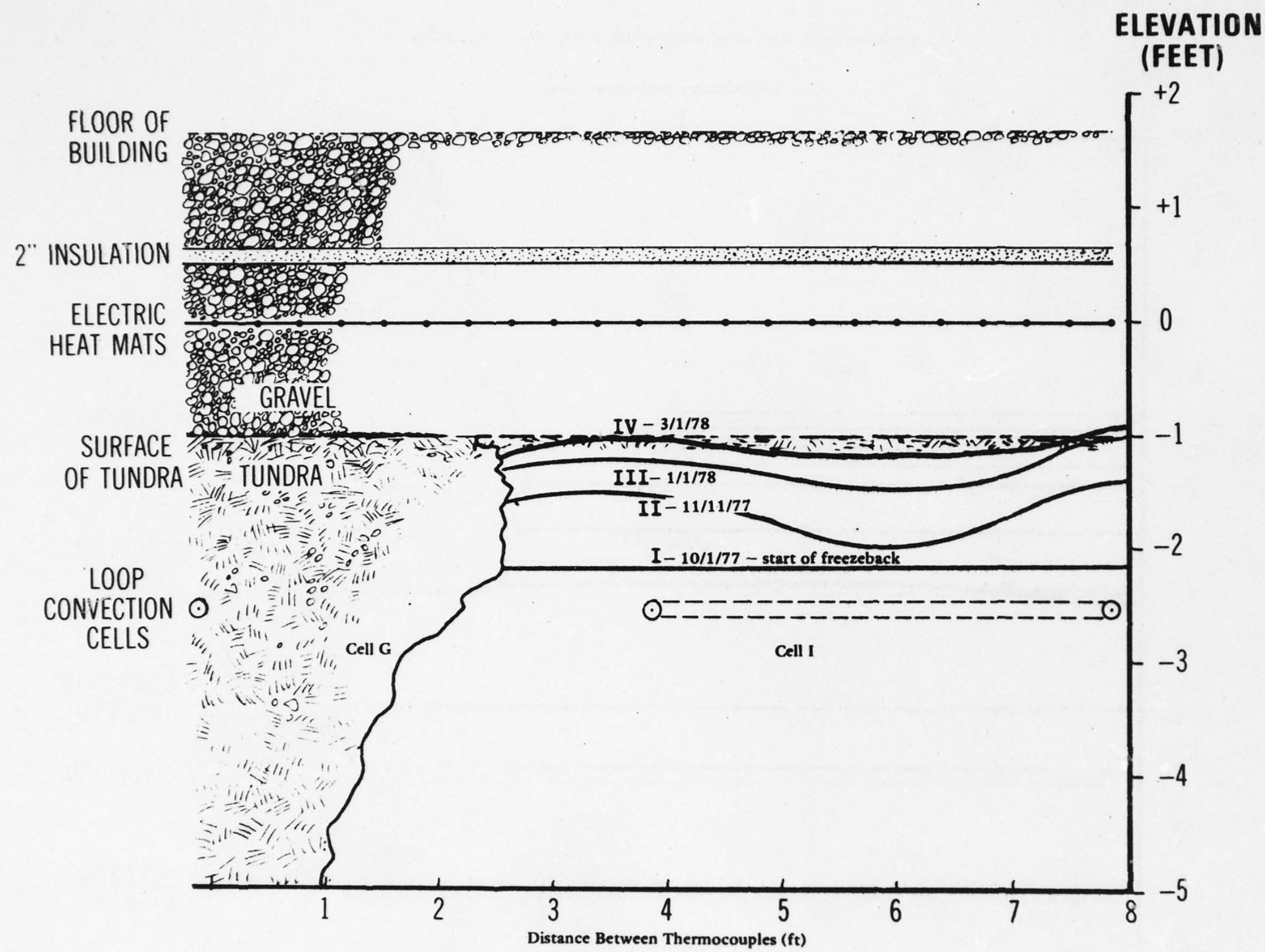

Figure 21. Freezeback during the 1977/78 winter.

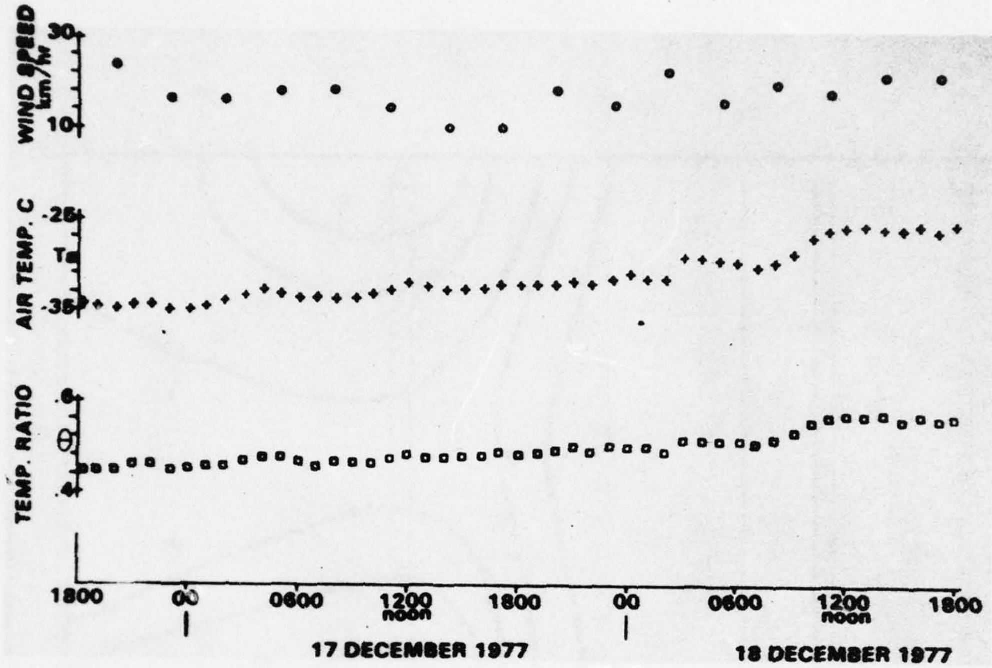

Figure 22. Convection cell temperature response during 48 hours, 17-18 December 1977.

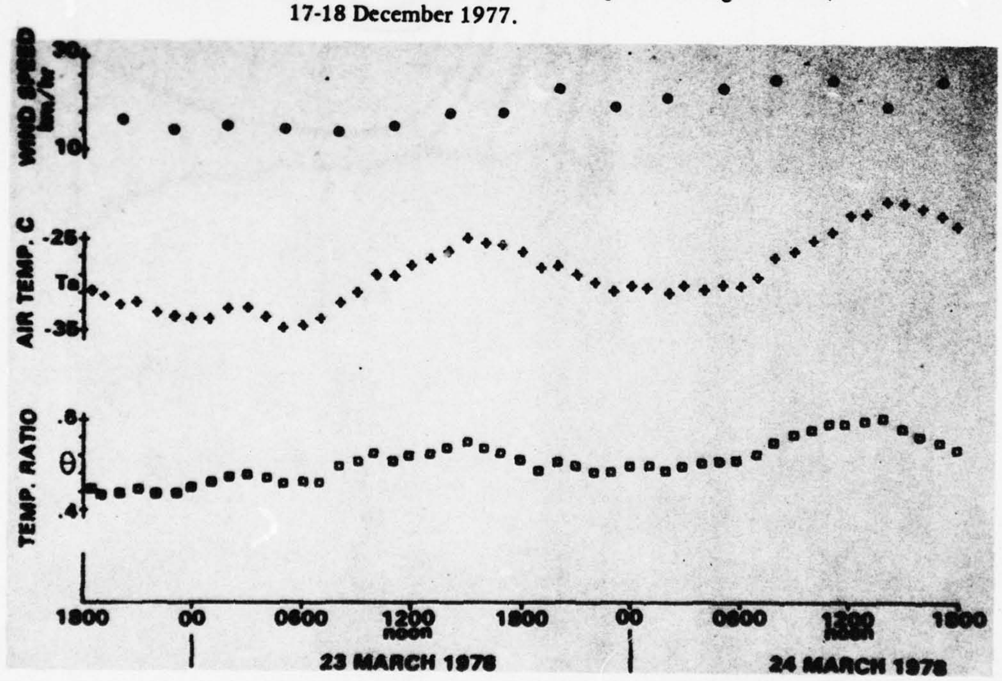

Figure 23. Convection cell temperature response during 48 hours, 23-24 March 1978.

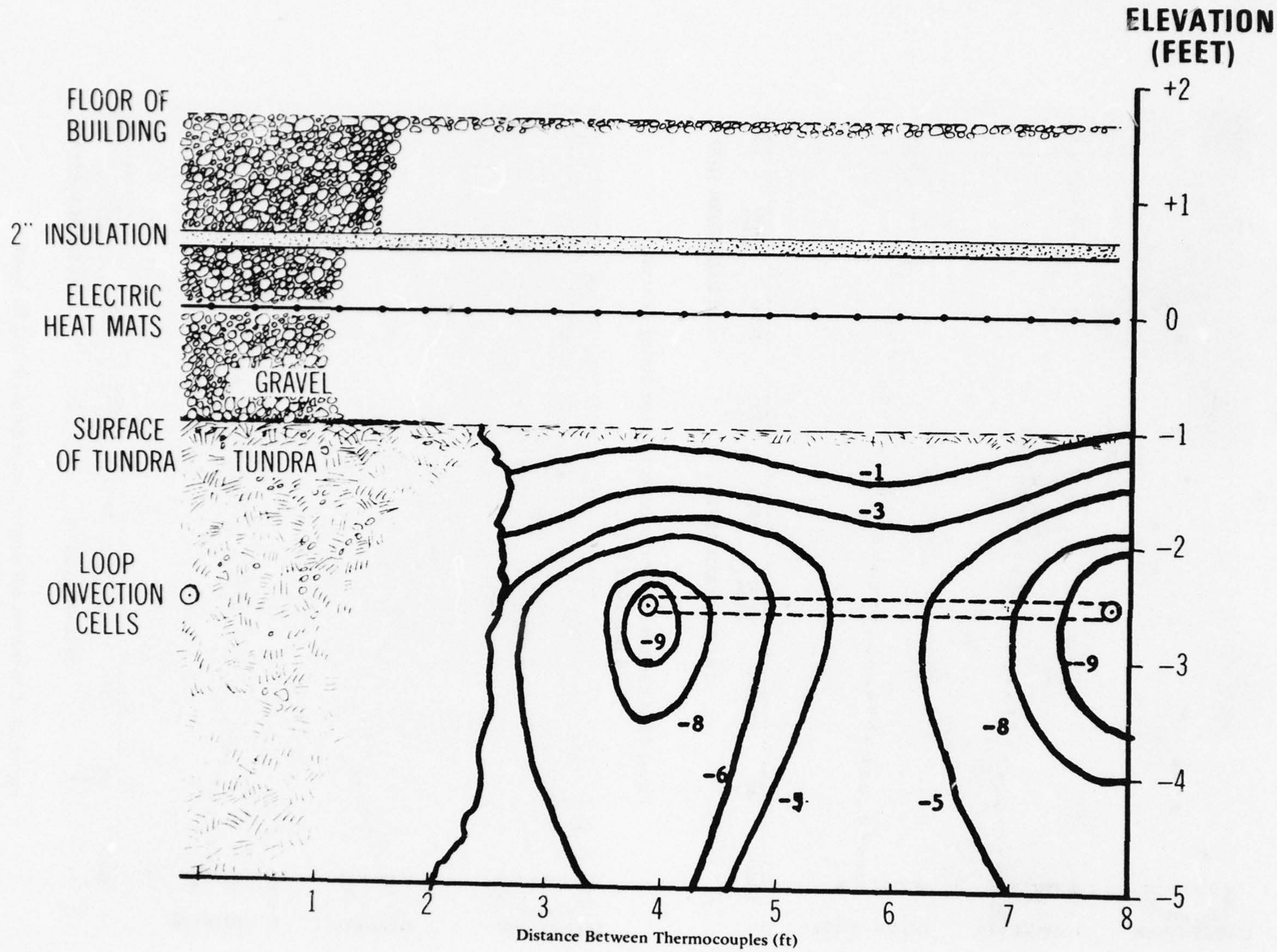

Figure 24. Isotherms around cell I, December 1977.

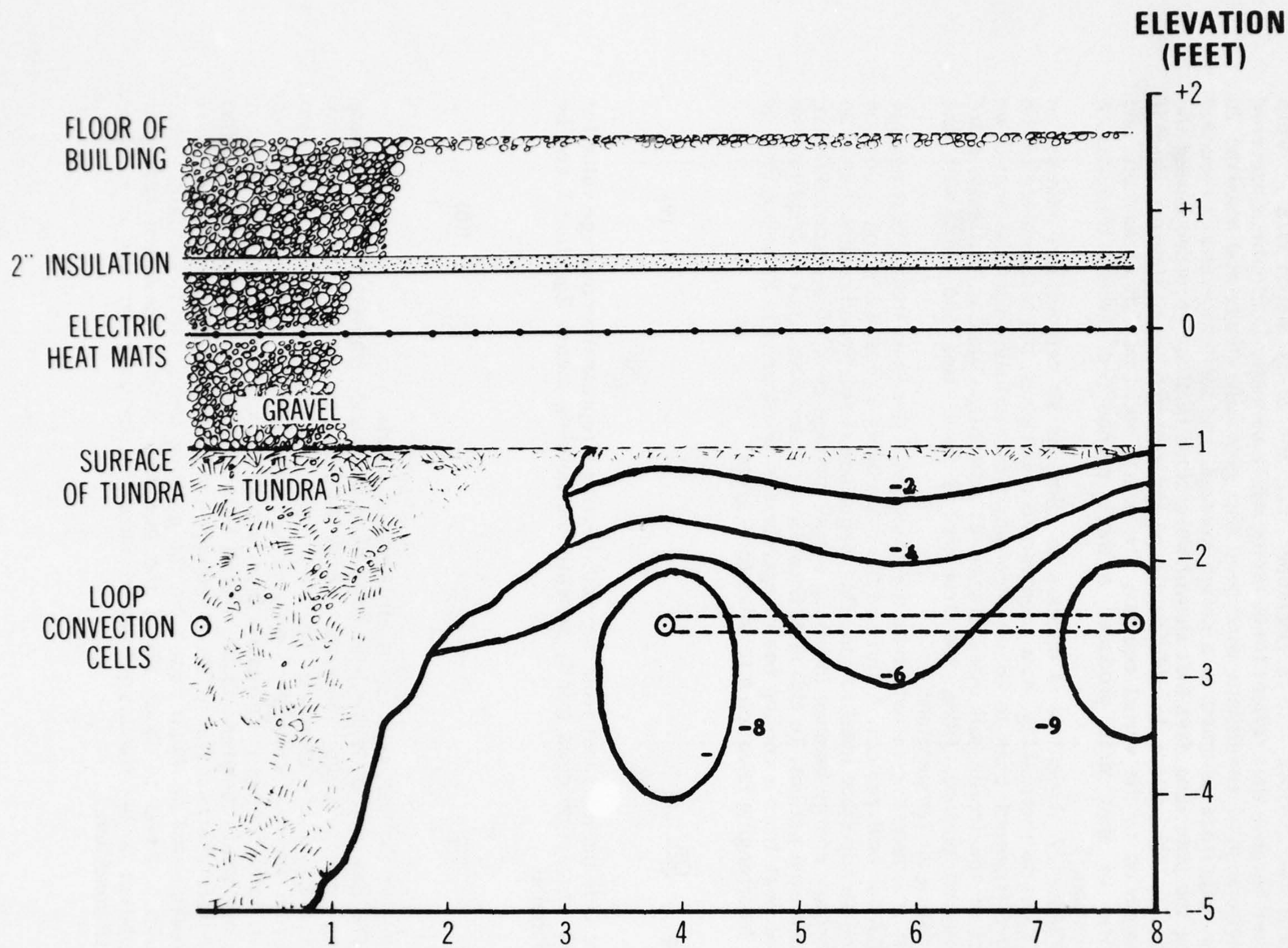

Figure 25. Isotherms around cell I, March 1978.

The two periods - 16-18 December 1977 and 22-24 March 1978 - were selected because they reflect times during which no major fluctuations occurred in environmental conditions: windspeed was generally steady and near the 20 km/hr magnitude assumed as a design average, and air temperatures recorded during the preceding days (not shown) were close to those recorded during the respective test periods. In addition, the period in March was of interest, since it corresponded to the vernal equinox. The nearly equal periods of daylight and darkness at that time produced a more pronounced diurnal temperature fluctuation.

Figure 22 shows how θ appears to climb as air temperature climbs, an effect due to thermal lag. As air temperature increases, the temperature of the liquid refrigerant tries to adjust accordingly but is delayed by the cool-down effect of the frozen soil mass. Figure 23 presents a similar, but even more pronounced picture. Here, the transient θ both rises and falls with the fluctuating air temperature.

It is interesting to note that the transient θ lies consistently between 0.4 and 0.6 for both periods. A value of 0.5 is probably a reasonable approximation for the steady-state idealization. This magnitude is additionally supported by an elementary energy balance involving actual average conditions recorded during the two time periods. To this end, Equation 4 can be used, since it describes the loss of heat from a cooling head (regardless of whether it is in an ice bath or soil). Rearranging Equation 4 to solve for θ gives

$$\theta = \frac{\dot{Q}R}{T_a} + 1 \qquad (9)$$

where $\dot{Q}$ is the heat lost from one cell. Letting θ represent an average value for the 13 convection cells totally beneath the building means Equation 9 can be rewritten as

$$\theta = \frac{\dot{Q}_t R}{13\,T_a} + 1 \qquad (10)$$

where $\dot{Q}_t$ is the heat rejected by all 13 cooling heads.

The quantity $\dot{Q}_t$ is the heat actually carried and removed by the subgrade cooling system. It represents the energy produced by the heat mats, less any losses and plus any additions. The major heat loss is upward through the foam insulation and was calculated as approximately 15% of the actual heat-mat output. Some change in $\dot{Q}_t$ results from adjustments in ground temperature, but these are small compared to the overall heat transfer. They are ignored in this elementary analysis. During the December period, heat from the electric mats is supplemented by latent heat from the growing freeze front. The latent heat addition is equal to about 5% of the heat-mat output. No latent heat was contributed during the March period since the freeze front was in a static growth condition.

The combined output of all heat-mat circuits is 28,500 watts. During both 2-day periods, the mats were active 50% of the time. This percentage represents a weighted average of all eight circuits. The heat rejected by the cooling heads in December, taking into consideration "on" time, upward losses, and latent heat additions, is

$$\dot{Q}_t = (28{,}500)\,(0.5)\,(0.85)\,(1.05) = 12{,}700 \text{ watts}$$

When this quantity is substituted into Equation 10, along with an average air temperature of -30C and R value of 0.012C/watt, the computed value of θ is

$$\theta = \frac{(12{,}700)\,(0.012)}{(13)\,(-30)} + 1 = 0.61$$

The heat rejected in March is

$$\dot{Q}_t = (28{,}500)\,(0.5)\,(0.85) = 12{,}100 \text{ watts}$$

Evaluating Equation 10 for this heat output and average air temperature of -28C gives

$$\theta = \frac{(12{,}200)\,(0.012)}{(13)\,(-28)} + 1 = 0.60$$

It is interesting to note that the two values of θ are very close to each other and also within the range of values recorded during the two separate 48-hour test periods. In essence, the ratio θ is a measure of convection cell heat-exchanger efficiency. It represents the cooling capability of a convection cell compared to the maximum quantity of cooling available - that is, the degrees of air temperature centigrade below 0C. Thus, it is reasonable to say that the heat exchangers used in the subgrade cooling experiment utilize on the average about half the available winter cold sink for permafrost freezeback and cool down.

Deep Temperature Data

One important aspect of the experimental cooling system, which to date has not been addressed, is its long-term effect upon the subgrade temperature regime. Because the convection cell is a thermal-resistance device and temperatures realized along the heat-intake pipe are not as cold as the ambient air, one would expect with time a general warming up of the permafrost beneath the building. Figure 26 presents temperature data at the 25-foot depth for strings 1 and 3, which are located, respectively, in the natural ground outside the building and beneath the center of the building (where there is the most warming by the electric heat mats). Figure 18 shows the locations of these strings. As anticipated, temperatures within the natural ground are consistently colder at depth than those beneath the center of the building. The peak cold temperatures actually occur in July, reflecting that at the 25-foot depth there

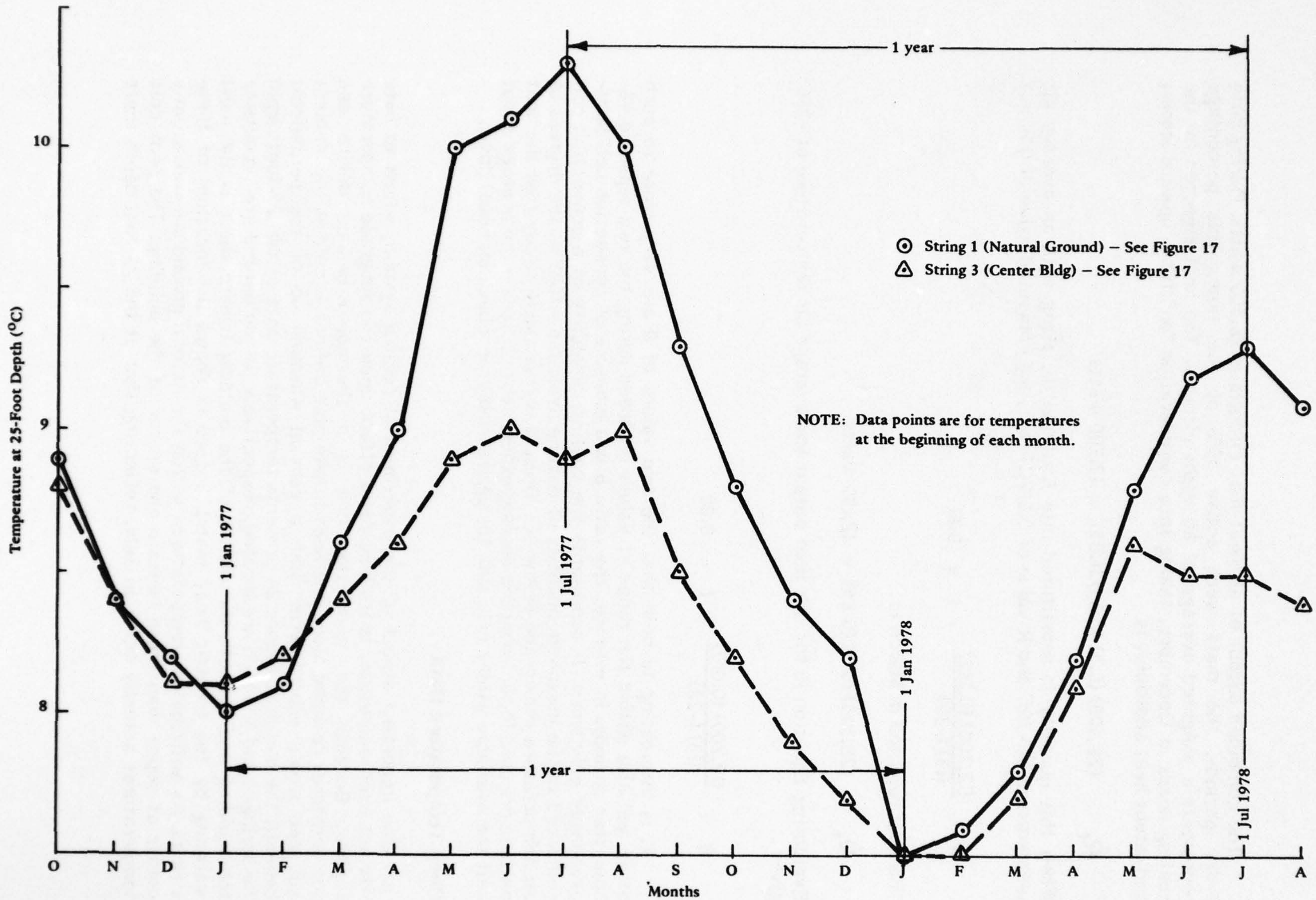

Figure 26. Deep temperature data for thermocouple strings in the natural ground and beneath the center of the building.

is approximately a 6-month time lag in temperature penetration. Also, in July, the temperature difference between the two deep locations reaches its maximum. More important, however, are the temperature highs that occur in January. During this period natural-ground and center-position temperatures nearly converge, indicating that in the long run (extrapolating from just 2 years of operational data), there may be no net warming of the subgrade. This is due in part to cooling by the surrounding natural permafrost but is also due to the nature of the simulation, which limits heat input to the ground by the modeling of an insulated floor system. Thus, while summer thaw penetration beneath the structure is restricted to about 1 foot, the active layer in the surrounding natural soils is more on the order of 18 inches or more, which is typical of the Barrow area. In short, the warmer-than-air-temperature condition along the heat-intake pipes during the winter is offset by the reduced heat input beneath the building during the summer.

Level Data

The heat-intake pipes are buried in ice-rich frozen silts, thus it is not surprising to find a small cyclical movement of the floor and foundation resulting from summer thaw and winter freezeback. Tables 3 and 4 present level measurements (in feet) referenced to the previously described stable benchmark. As anticipated, both the floor and foundation exhibit similar patterns of movement throughout the year, with settlement occurring in the summer months and heaving occurring during winter freezeback.

Table 3 presents level data for points along the wooden sill foundation. It should be noted that maximum recorded settlement and heave are both on the order of 1-1/2 inches, although in most instances level changes at the various points are substantially less. Table 4 presents level data for points located along the Marston matting floor. Floor movement is slightly greater than that of the foundation (which is to be expected since the floor is more lightly loaded and directly above the thaw/freeze zone), with a maximum heave and settlement of just under 2 inches. Although such movement of the foundation and floor systems is not ideal, the settlement that would have occurred if the massive ice present below had thawed could have been spectacular, to say the least.

The interested reader is encouraged to consult Reference 6 for a more complete account of the level data program and for speculations as to some of the causes of variations in behavior.

Heat Mats

The total heat production of the resistance mats between 7 March 1977 (when all circuits were fitted with hour-meters) and 5 September 1978 has been 8×10^4 kWh. This quantity represents a 21% "on" time for the heating system, based on a weighted average of all eight circuits. Of course, it should be remembered that the weighted average calculated on a yearly basis is somewhat greater, since the 1-1/2-year observation period described includes an unproportionately large amount of summer time.

Table 3. Foundation Elevations Referenced to Stable Benchmark

Level Station	Elevations		Elevations and deviations (ft) on following dates–								
	9/19/76	11/21/76	Deviation[a] Between 9/19-11/21	Elevation 5/14/77	Deviation[a] Between 11/21-5/14	Elevation 9/5/77	Deviation[a] Between 5/14-9/5	Elevation 5/19/78	Deviation[a] Between 9/5-5/19	Elevation 9/6/78	Deviation[a] Between 5/19-9/6
1	-2.73	-2.663	+0.07	-2.642	+0.021	-2.672	-0.03	-2.569	+0.103	-2.590	-0.021
2	-2.77	-2.695	+0.07	-2.702	-0.007	-2.745	-0.043	-2.672	+0.073	-2.710	-0.038
3	-2.77	-2.704	+0.07	-2.695	+0.009	-2.762	-0.067	-2.695	+0.067	-2.750	-0.055
4	-2.74	-2.689	+0.05	-2.659	+0.03	-2.762	-0.103	-2.722	+0.040	-2.765	-0.043
5	-2.72	-2.671	+0.05	-2.671	0	-2.736	-0.065	-2.687	+0.049	-2.755	-0.068
6	-2.83	-2.732	+0.10	–	–	-2.778	–	-2.652	+0.126	-2.78	-0.128
7	-2.74	-2.667	+0.07	-2.658	+0.009	-2.791	-0.133	-2.712	+0.079	-2.842	-0.13
8	-2.76	-2.690	+0.07	-2.667	+0.023	-2.796	-0.129	-2.740	+0.056	-2.825	-0.085
9	-2.80	-2.731	+0.07	-2.722	+0.009	-2.823	-0.101	-2.770	+0.053	-2.830	-0.06
10	-2.76	-2.688	+0.07	-2.679	+0.009	-2.813	-0.134	-2.682	+0.131	-2.755	-0.073
11	-2.75	-2.655	+0.09	-2.647	+0.008	-2.712	-0.065	-2.605	+0.107	-2.670	-0.065
12	-2.76	-2.667	+0.09	-2.671	-0.004	-2.681	-0.01	-2.561	+0.120	-2.575	-0.014

[a] Positive deviation indicates heave; negative deviation indicates settlement.

Table 4. Floor Elevations Referenced to Stable Benchmark

Level Station	Elevations			Elevations and deviations (ft) on following date–							
	12/6/76	5/14/77	Deviation[a] Between 12/6-5/14	Elevation 9/5/77	Deviation[a] Between 5/14-9/5	Elevation 12/1/77	Deviation[a] Between 9/5-12/1	Elevation 5/19/78	Deviation[a] Between 12/1-5/19	Elevation 9/6/78	Deviation[a] Between 5/19-9/6
1	-1.491	-1.391	+0.100	-1.485	-0.094	-1.401	+0.084	-1.349	+0.052	-1.542	-0.193
2	-1.518	-1.454	+0.064	-1.591	-0.137	-1.523	+0.068	-1.455	+0.068	-1.655	-0.200
3	-1.506	-1.402	+0.104	-1.547	-0.145	-1.439	+0.108	-1.413	+0.026	-1.618	-0.205
4	-1.409	–	–	–	–	–	–	–	–	-1.540	–
5	-1.290	–	–	–	–	–	–	-1.205	–	-1.387	-0.182
6	-1.441	-1.340	+0.101	-1.587	-0.147	-1.485	+0.102	–	–	-1.648	–
7	-1.469	–	–	–	–	–	–	–	–	-1.600	–
8	-1.559	-1.426	+0.133	-1.602	-0.176	-1.455	+0.147	-1.432	+0.023	-1.618	-0.186
9	-1.536	-1.407	+0.129	-1.598	-0.191	-1.470	+0.128	–	–	-1.630	–
10	-1.604	-1.496	+0.108	-1.642	-0.146	-1.541	+0.101	–	–	-1.677	–
11	-1.519	-1.348	+0.171	-1.458	-0.110	-1.395	+0.063	-1.350	+0.045	-1.505	-0.155
12	-1.466	-1.338	+0.128	-1.470	-0.132	-1.380	+0.090	-1.348	+0.032	-1.513	-0.165
13	-1.560	-1.388	+0.172	-1.498	-0.110	-1.400	+0.098	-1.370	+0.030	-1.535	-0.165
14	-1.498	-1.390	+0.108	-1.482	-0.092	-1.397	+0.085	–	–	-1.509	–
15	-1.421	-1.351	+0.07	-1.548	-0.197	-1.473	+0.075	-1.391	+0.082	-1.507	-0.116

[a]Positive deviation indicates heave; negative deviation indicates settlement.

MODIFICATIONS

The cooling heads were designed in a parallel arrangement to produce a loop of unbalanced heat-exchange surface area. However, an interesting phenomenon was discovered shortly after activation. During periods of warming weather, with air temperature rising above the temperature of the circulating refrigerant, a reversal of flow would sometimes occur within some of the loops. This in itself was not too surprising, since it was anticipated that transient disturbances would interfere with established flow patterns. However, what was surprising is that the condition would sometimes persist for weeks at a time, even after the return of colder air temperatures. Although there was no noticeable decrease in heat-exchanger performance, there was the fear that similar flow might continue during the summer months, thereby causing the convection cells to act as heat pumps to warm the subgrade. During March 1977, a number of convection cells were modified so that the direction of flow could be checked on location by visual observation, and all cells were fitted with an in-line shutoff valve.* A long view tube was installed in the warm riser of cooling head for cell I, and smaller sight glasses were installed in cells E, F, J, and K.

During December 1977, 3 of the 15 liquid natural convection cells were further modified to include a forced convection mode by addition of small immersible pumps. It was anticipated that this would improve the heat-exchange capacity of the cells, thereby permitting a building design with less insulation in the floor, or possibly improving performance to such a degree that the system could be extended to warmer, more marginal polar locations. A pump was desired that would not interfere with the natural convection circulation when de-energized. Such a unit was located - an "immersible" pump which could be installed in the existing standpipe at the top of the "warm" riser of the cooling head. The pump draws its suction from the warm riser by means of a 2-foot-long, 3/4-inch-diam suction pipe and directs its approximately 10-gpm discharge into the horizontal finned pipe member of the cooling head. Adequate clearance remains for the natural convection flow of liquid around the pump when it is not operating.

Three neighboring heat exchangers were equipped with pumps, the outer two serving more or less as buffers for the middle cell, which is instrumented. Cells F, H, and J were chosen for modification since cell H already had thermocouples attached to the warm and cold arms of the buried heat-intake pipe (something necessary to measure performance but impractical to add after installation). In order to mount the pumps, the 22-inch-long, 4-inch-diam standpipes were removed and replaced by shorter standpipes with brackets. After mounting, the pumps were covered with cans to minimize the ingestion of snow by the motor-powered cooling fans. All three pumps were wired to a single circuit breaker so they could be turned off during the summer season of above-freezing air temperature.

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*The fears of summer flow were unjustified. As originally predicted, all flow has ceased during the summer months when air temperature is above ground temperature. It has not been necessary to close any of the shutoff valves.

Most of the soil volume above the three modified cells is beneath heat mat circuits 2 and 8 so that, for all intent and purposes, the pump-equipped heat exchangers are isolated from the rest of the subgrade system. One mat in circuit 8 (mat 82) was entirely above the unmodified cells; it was rewired into adjacent circuit 7 to further minimize the chance for interference.

Instrumentation

Switching module boards were procured to allow addition of as many as 30 more thermocouples to the existing datalogging system in the building to monitor the performance of the pump-assisted convection cells, but difficulties in drilling precluded original plans for thermocouple strings.

Holes for vertical strings adjacent to cell H were drilled with a 2-1/2-inch-diam auger driven by a 1-inch electric drill motor. Since these holes penetrated material that had been backfilled into the trenches in which the convection cells had been placed, drilling was relatively easy until the natural ground (ice-rich frozen silt) was reached. Difficult penetration at that point forced hole limitations to a total depth of 6 inches below cell level. Table 5 lists the depths and designations of these thermocouples, and their locations are shown in plan view in Figure 27.

Since drilling by hand was so difficult, a proposed one-quarter-width thermocouple string could not be emplaced in this manner. Use of the CEL mobile B-40L drill vertically inside the building would have required removal of some paneling from the roof of the building to allow clearance for the mast of the drill. Rather than do this, a hole was slanted at 47 degrees from the vertical under the wall of the building from outside, and thermocouples placed as close as possible to the desired locations. These locations with thermocouple designations are shown in profile in Figure 28 and in plan in Figure 27. The thermocouple string at the edge of the building was slanted at 11 degrees from the vertical to clear the convection cell cooling heads and is shown in the same two figures.

Observations

The net result of pump operation after the first winter has been a <1C decrease in temperature in the assisted cells when compared to the unassisted cells. Although such performance is disappointing, it does not totally invalidate the concept of pump-assisted flow. It should be remembered that heat transfer in the unmodified convection cells is the result of natural convection forces, which in turn are dependent upon the temperature of the ambient air. The severe winters in the Barrow area result in a flow where the thermal resistance of the refrigerant is small compared to that of the cooling head. Thus, little improvement is realized from pump flow. However, under subarctic conditions winters are less cold, and the potential for improving performance by pump-assisted flow is enhanced.

It should be apparent that the pump-assisted convection cell has the potential of warming the ground during the summer. The units in the Barrow installation were turned off during a field trip in May 1978, before the onset of above-freezing air temperatures.

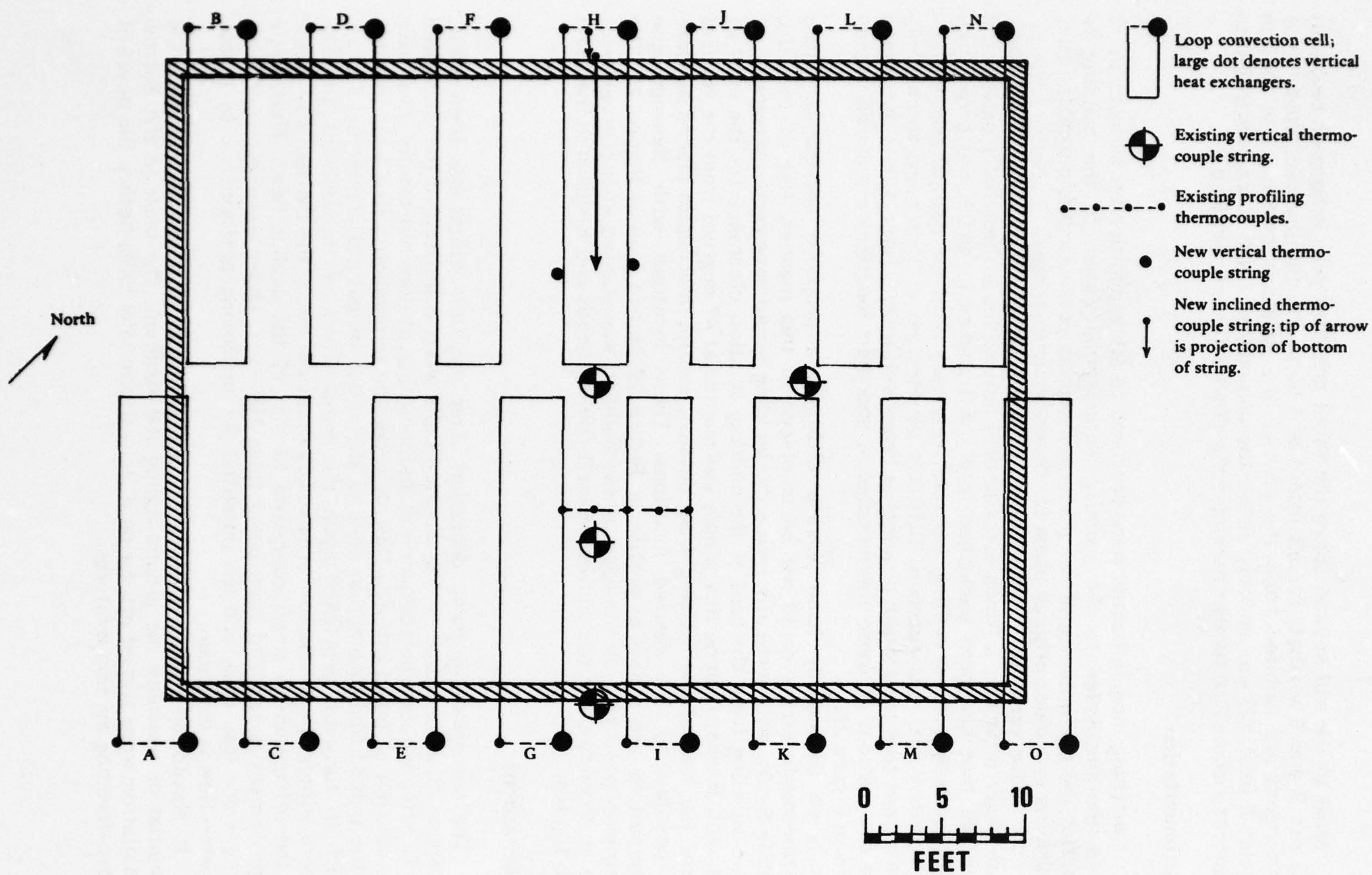
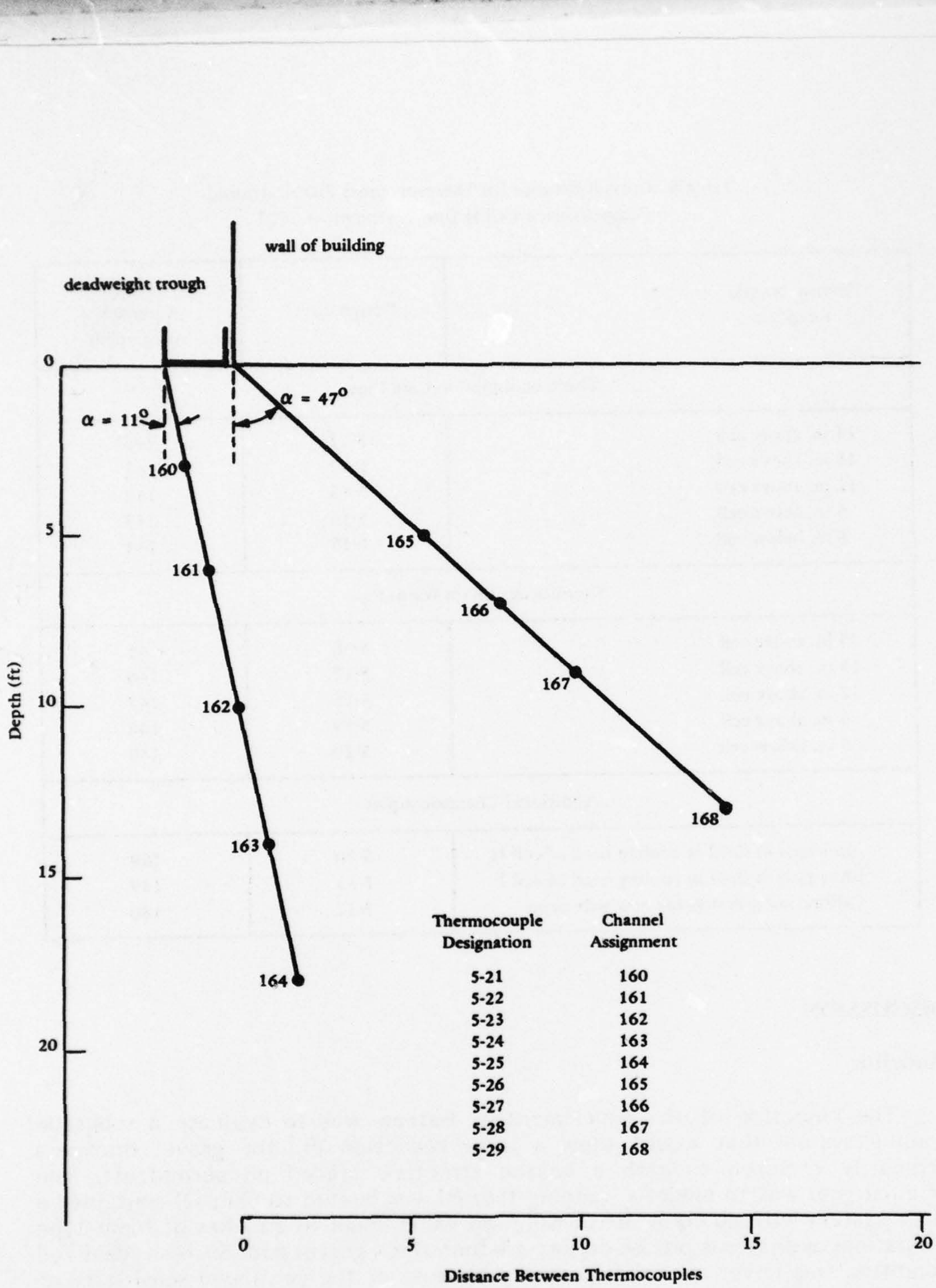


Figure 27. Location in plan of new thermocouple strings.



Thermocouple Designation	Channel Assignment
5-21	160
5-22	161
5-23	162
5-24	163
5-25	164
5-26	165
5-27	166
5-28	167
5-29	168

Figure 28. Location in elevation of new thermocouple strings.

Table 5. Cross Reference for Thermocouples Placed Around Pump-Assisted Cell H During December 1977

Thermocouple Location	Designation	Datalogger Channel Assignment
Thermocouples on Cold Pipe		
24 in. above cell	5-11	140
18 in. above cell	5-12	141
12 in. above cell	5-13	142
6 in. above cell	5-14	143
6 in. below cell	5-15	144
Thermocouples on Warm Pipe		
24 in. above cell	5-16	145
18 in. above cell	5-17	146
12 in. above cell	5-18	147
6 in. above cell	5-19	148
6 in. below cell	5-20	149
Additional Thermocouples		
Immersed in fluid in cooling head of cell H	5-30	169
Immersed in fluid in cooling head of cell I	5-31	139
Calibration junction for new wire type	5-32	180

DISCUSSION

Modeling

The objective of the experiment at Barrow was to evaluate a subgrade cooling system that would allow a large reduction in the gravel thickness ordinarily required beneath a heated structure placed on permafrost. The original goal was to model a building that (1) was heated to 68F; (2) contained a floor system with an equivalent insulation value equal to 2 inches of foam-type insulation; and (3) was placed on just a 1-foot-thick gravel pad. Such an idealized condition was never realized, partially because of the continued sensitivity of thermostat calibration to ambient air temperature, but mainly because it is simply not feasible to model a constant air temperature boundary condition (i.e., 68F inside the building) with the configuration of heat mats used. The capillary bulbs controlling the individual circuits were buried in the gravel pad, midway between the heat mats and the tundra surface. It was necessary to

select a single control temperature at capillary-bulb depth. The thermostats then maintained this temperature by controlling the "on" time of the heat-mat circuits. If, instead, the air space within the building were actually heated, then the temperature at capillary-bulb depth would be forced to fluctuate up and down as the freeze front periodically retreated and advanced throughout the year. In other words, the use of resistance heating as an energy source tended to impose an unnatural boundary condition.

As it turns out, the operating temperature selected for the thermostats most accurately models the summer season; thus, during this time appropriate amounts of heat are released into the ground. As a result, thaw penetration is near the value predicted initially. As the freeze front advances upward during the winter season, the deviation away from "model" conditions increases dramatically. During the March 22-24 observation period, for instance, the average 12,000-watt heat influx is on the order of five to six times greater than that which exists for a heated building with an insulated floor. It is indeed gratifying to know that the subgrade cooling system can handle this greater heat removal. Although the heat-transfer model (as originally conceived) has failed, the experimental subgrade cooling system itself has been quite successful, both in concept and practice.

Settlement

The building at Barrow is located on just enough gravel to elevate it above summer surface water on the tundra. The heat-intake pipes are buried in ice-rich frozen silts; as a result, a small cyclical movement of the floor and foundation takes place. Although such performance is not ideal, the settlement that would have occurred if the massive ice present below had thawed could have been spectacular, to say the least. Perhaps the next step in foundation construction is to combine the gravel-pad and subgrade-cooling concepts. Reference 14 suggests placing self-refrigerated heat exchangers within a gravel pad thick enough to handle summer thaw and winter freezeback. In this way, freeze/thaw action is restricted to a thaw-stable, nonfrost-susceptible buffer, and seasonal heave and settlement should be held to a minimum. Since the buffer material must act as a heat sink, it should have as high a latent heat content as possible. This basically involves high moisture content, which in turn dictates that the material be as fine-grained as possible without being frost-susceptible. It may also be possible to maintain a saturated condition in the soil by placing a dike composed of impervious soils around the gravel pad.

CONCLUSIONS

In the past, three basic approaches to foundation design are employed in placing heated structures on frozen soils. The simplest approach is to allow the soil to thaw and accept the resulting settlement. Although such a method may be a satisfactory solution when the underlying frozen soils are thaw-stable, this condition is the exception rather than the rule. A second alternative is to modify the site by pre-thawing or excavating in-situ materials. However, this

method can be difficult and costly where thick deposits of non-thaw-stable soils are present. The third and most satisfactory approach is to keep the soil frozen by placing the structure on either a thick gravel pad or on an elevated-post foundation. With the latter, a free air-space is provided beneath the floor to reduce the influx of heat from the building into the soil and to permit the cold winter air to cool the bearing soils.

The post-and-pad approach to foundation design also has shortcomings. It is very expensive, and most often it is not practical to elevate heavily loaded structures such as heavy-equipment garages and aircraft hangars on piles. Likewise, in areas where gravel is scarce, transportation costs for importation can be prohibitive. Even along the coast where gravel has traditionally been mined, removal of that material has led to erosion and shoreline regression and in some areas is no longer permitted. The CEL subgrade-cooling approach provides a means of reducing gravel requirements while at the same time removing the necessity for an elevated air space. Since the heat removal capability is contained within the surficial soils, structures can be successfully located at grade.

The convection cell installation was designed entirely as an experiment since the CEL building does not require heating in its function of equipment storage. As an experimental effort it should be viewed as a success. After nearly 2 years of operation, the system has demonstrated a potential for subgrade cooling and preservation of ice-rich permafrost beneath a heated building. It is hoped that the concept will be embraced by industry and considered as an option in future cold weather design and construction projects.

RECOMMENDATIONS

1. The subgrade cooling installation was designed as an experimental effort, and no consideration has been given to monetary advantages or disadvantages. An economic analysis should be conducted on a geographical basis to determine potential savings for subgrade systems compared to conventional pad-and-post construction.

2. The CEL installation used liquid natural convection cells primarily because of prior experience, ease of assembly, and availability of hardware. However, two-phase cells offer the advantage of lightweight construction. It is recommended that in the future a comparison be made of the devices in terms of initial cost, ease of installation, reliability, and maintenance.

ACKNOWLEDGMENTS

The author wishes to acknowledge Mr. John E. Cronin, who was project engineer in charge of conducting the subsurface geological investigation and erecting the building and whose earlier Technical Memorandums are referenced frequently in this report. The author also wishes to thank Ms Cathleen J. Cavin, NARL technician in charge of weekly data gathering. Her prompt ano timely services have been greatly appreciated.

REFERENCES

1. J. C. LaBelle. "Fill materials resources between Barrow and the Colville River, Arctic coastal plain, Northern Alaska," in Proceedings, Third International Conference on Port and Ocean Engineering under Arctic Conditions, Fairbanks, Alaska, Aug 11-15, 1975.

2. J. D. Hume, M. Schalk, and P. W. Hume. "Short-term climate changes and coastal erosion, Barrow, Alaska," Arctic, vol 25, no. 4, 1972, pp 272-278.

3. Civil Engineering Laboratory. Technical Memorandum M-61-76-6: Investigation of CEL experimental building site, NARL, Barrow, Alaska, by J. E. Cronin. Port Hueneme, Calif., Apr 1976.

4._______. Technical Memorandum M-61-77-1: The CEL experimental building and subgrade cooling system, Barrow, Alaska - construction and initial performance, by J. E. Cronin. Port Hueneme, Calif., Feb 1977.

5._______.Technical Memorandum M-61-77-12: Modifications to the CEL experimental building and subgrade cooling system, Barrow, Alaska, by J. E. Cronin. Port Hueneme, Calif., Apr 1977.

6._______. Technical Memorandum M-61-78-1: The CEL experimental building and subgrade cooling system, Barrow, Alaska - first year performance, by J. E. Cronin. Port Hueneme, Calif., Jan 1978.

7. J. E. Cronin. "A liquid natural convection concept for building subgrade cooling," in Proceedings, Second International Symposium on Cold Regions Engineering, Fairbanks, Alaska, Aug 12-14, 1976.

8. Civil Engineering Laboratory. Technical Report R-811: Ice engineering - quantification of subsurface ice thickening techniques, by J. L. Barthelemy. Port Hueneme, Calif., May 1974.

9._______.Technical Report R-845: Ice engineering - a heat sink method for subsurface ice thickening, by J. L. Barthelemy. Port Hueneme, Calif., Jul 1976.

10. J. L. Barthelemy. Technical Publication 75-WA/HT-96: A heat sink concept for subsurface ice thickening. New York, N.Y., American Society of Mechanical Engineers, Jan 1976.

11. F. J. Sanger. "Degree-days and heat conduction in soils," in Proceedings, Permafrost International Conference, Lafayette, Ind., Nov 11-15, 1963.

12. Naval Civil Engineering Laboratory. Technical Report R-754: Thawing of permafrost at Barrow, Alaska - a method of stabilizing floor foundations, by R. A. Paige and J. A. O'Brien. Port Hueneme, Calif., Jan 1972.

13. J. L . Barthelemy. "Performance of a natural convection heat exchange system for subgrade cooling of permafrost," prepared for Building Under Cold Climates and on Permafrost Seminar, Leningrad, USSR, Oct 2-7, 1978.

14. A. Phukan, R. D. Abbott, and J. E. Cronin, "Self-refrigerated gravel pad foundations in frozen soil," paper presented at Specialty Conference on Cold Regions Engineering and Construction, Anchorage, Alaska, May 17-19, 1978.

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NAVCOMMAREAMSTRSTA SCE Unit 1 Naples Italy
NAVCOMMSTA Code 401 Nea Makri, Greece; PWO, Exmouth, Australia
NAVEDTRAPRODEVCEN Tech. Library
NAVENVIRHLTHCEN CO, Cincinnati, OH
NAVEODFAC Code 605, Indian Head MD
NAVFAC PWO, Barbados
NAVFACENGCOM Code 043 Alexandria, VA; Code 044 Alexandria, VA; Code 0451 Alexandria, VA; Code 0454B Alexandria, Va; Code 1023 (T. Stevens) Alexandria, VA; Morrison Yap, Caroline Is.; P W Brewer Alexandria, VA
NAVFACENGCOM - CHES DIV. FPO-1 (Spencer) Wash, DC
NAVFACENGCOM - LANT DIV. RDT&ELO 102, Norfolk VA
NAVFACENGCOM - NORTH DIV. Code 1028, RDT&ELO, Philadelphia PA
NAVFACENGCOM - PAC DIV. Code 402, RDT&E, Pearl Harbor HI; Commander, Pearl Harbor, HI
NAVFACENGCOM - WEST DIV. Code 04B; 09P/20; RDT&ELO Code 2011 San Bruno, CA
NAVFACENGCOM CONTRACT OICC, Southwest Pac, Manila, PI; ROICC (LCDR J.G. Leech), Subic Bay, R.P.; ROICC, Keflavik, Iceland
NAVOCEANO Code 1600 Bay St. Louis, MS
NAVOCEANSYSCEN Code 52 (H. Talkington) San Diego CA; Code 6565 (Tech. Lib.), San Diego CA
NAVPETRES Director, Washington DC
NAVPGSCOL E. Thornton, Monterey CA
NAVPHIBASE CO, ACB 2 Norfolk, VA; Code S3T, Norfolk VA
NAVSEASYSCOM Code OOC (LT R. MacDougal), Washington DC
NAVSHIPYD Tech Library, Vallejo, CA
NAVSTA PWO, Mayport FL; Utilities Engr Off. (LTJG A.S. Ritchie), Rota Spain
NAVSUPPACT CO, Brooklyn NY; Code 413, Seattle WA; LTJG McGarrah, Vallejo CA
NAVSURFWPNCEN PWO, White Oak, Silver Spring, MD; Silver Spring MD
NAVTECHTRACEN SCE, Pensacola FL
NAVWPNCEN Code 2636 (W. Bonner), China Lake CA
NAVWPNSTA EARLE PW Office (Code 09C1) Yorktown, VA; PWO, Seal Beach CA
NAVWPNSUPPCEN Code 09 Crane IN
NCBC CEL AOIC Port Hueneme CA; Code 10 Davisville, RI; Code 155, Port Hueneme CA; Code 156, Port Hueneme,

CA
NCR 20, Commander
NORDA Code 410 Bay St. Louis, MS
NSF Polar Info Service
NTC Code 54 (ENS P. G. Jackel), Orlando FL
NUSC Code 131 New London, CT
OCEANAV Mangmt Info Div., Arlington VA
ONR BROFF, CO Boston MA; Code 461, Arlington VA (McGregor); Code 481, Arlington VA; Code 481, Bay St. Louis, MS; Code 700F Arlington VA
PMTC Pat. Counsel, Point Mugu CA
PWC CO Norfolk, VA; CO, Great Lakes IL; CO, Oakland CA; Code 120C (Library) San Diego, CA; Code 220.1, Norfolk VA; Code 400, Pearl Harbor, HI
U.S. MERCHANT MARINE ACADEMY Kings Point, NY (Reprint Custodian)
US DEPT OF COMMERCE NOAA, Pacific Marine Center, Seattle WA
USCG (G-MP-3/USP/82) Washington Dc
USCG R&D CENTER Tech. Dir. Groton, CT
USNA Ocean Sys. Eng Dept (Dr. Monney) Annapolis, MD; Oceanography Dept (Hoffman) Annapolis MD
LIBRARY OF CONGRESS WASHINGTON, DC (SCIENCES & TECH DIV)
MICHIGAN TECHNOLOGICAL UNIVERSITY Houghton, MI (Haas)
MIT Cambridge MA; Cambridge MA (Rm 10-500, Tech. Reports, Engr. Lib.)
NATL ACADEMY OF ENG. ALEXANDRIA, VA (SEARLE, JR.)
UNIV. NOTRE DAME Katona, Notre Dame, IN
OREGON STATE UNIVERSITY CORVALLIS, OR (CE DEPT, BELL); Corvalis OR (School of Oceanography)
PURDUE UNIVERSITY Lafayette, IN (Altschaeffl); Lafayette, IN (CE Engr. Lib)
STANFORD UNIVERSITY STANFORD, CA (DOUGLAS)
TEXAS A&M UNIVERSITY W.B. Ledbetter College Station, TX
UNIVERSITY OF ALASKA Arctic Data Center; Doc Collections Fairbanks, AK
UNIVERSITY OF CALIFORNIA BERKELEY, CA (CE DEPT, GERWICK)
UNIVERSITY OF ILLINOIS Metz Ref Rm, Urbana IL; URBANA, IL (NEWMARK)
UNIVERSITY OF NEBRASKA-LINCOLN Lincoln, NE (Ross Ice Shelf Proj.)
UNIVERSITY OF WASHINGTON (FH-10, D. Carlson) Seattle, WA; SEATTLE, WA (APPLIED PHYSICS LAB); SEATTLE, WA (OCEAN ENG RSCH LAB, GRAY); Seattle WA (E. Linger)
AMOCO PROD. CO (Cox) Res. Dept, Tulsa, OK
ATLANTIC RICHFIELD CO. DALLAS, TX (SMITH)
BECHTEL CORP. SAN FRANCISCO, CA (PHELPS)
BOUW KAMP INC Berkeley
CANADA Library, Calgary, Alberta; Lockheed Petrol. Srv. Ltd., New Westminster BC; Mem Univ Newfoundland (Chari), St Johns; Surveyor, Nenninger & Chenevert Inc., Montreal; Trans-Mnt Oil Pipe Lone Corp. Vancouver, BC Canada; Warnock Hersey Prof. Srv Ltd, La Sale, Quebec
CHEVRON OIL FIELD RESEARCH CO. LA HABRA, CA (BROOKS)
CONCRETE TECHNOLOGY CORP. TACOMA, WA (ANDERSON)
GULF SCI.& TECH CO (Vaudrey), Houston, TX
JAMES CO. R. Girdley, Orlando FL
MARATHON OIL CO Houston TX (C. Seay)
MARINE CONCRETE STRUCTURES INC. MEFAIRIE, LA (INGRAHAM)
NORWAY J. Creed, Ski
RAYMOND INTERNATIONAL INC. E Colle Soil Tech Dept, Pennsauken, NJ
SHELL DEVELOPMENT CO. Houston TX (C. Sellars Jr.); Houston, TX (Earle)
SHELL OIL CO. Houston TX (R. de Castongrene); I. Boaz, Houston TX
SWEDEN VBB (Library), Stockholm
UNITED KINGDOM Cement & Concrete Assoc Wexham Springs, Slough Bucks; Cement & Concrete Assoc. (Lit. Ex), Bucks; R. Browne, Southall, Middlesex; Taylor, Woodrow Constr (014P), Southall, Middlesex
BRAHTZ La Jolla, CA
BULLOCK La Canada
R.F. BESIER Old Saybrook CT
CEC Parisi, Anthony M., LT